Beamlines
for Fixed Target Experiments

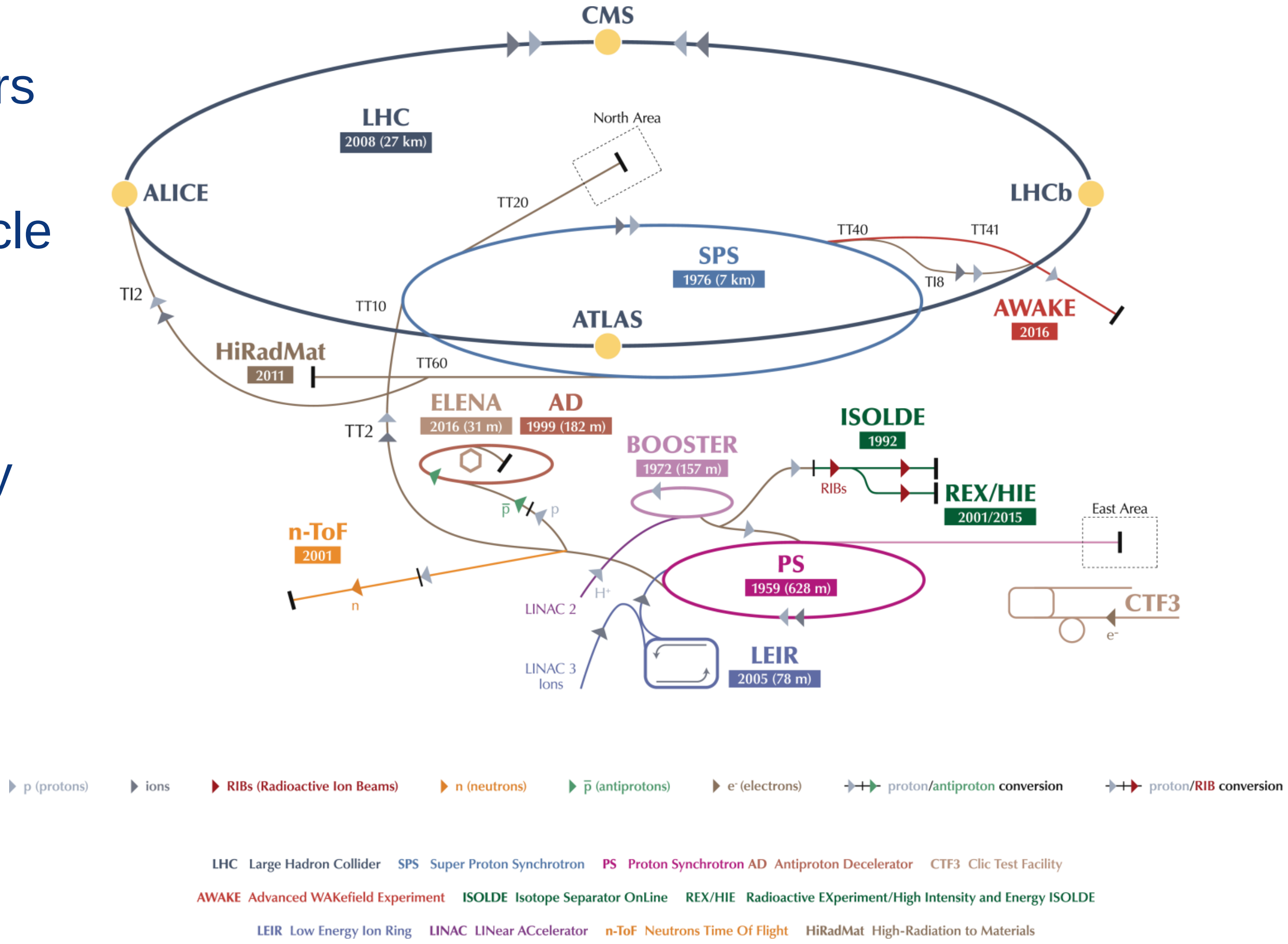
Alexander Gerbershagen

On behalf of CERN BE-EA-LE

a.ge@cern.ch

Overview

- Introduction:
  Purpose and users
- Targets and particle production
- Design of secondary/tertiary beamlines
- Experiments at CERN



Introduction

Fixed Target (FT) setup

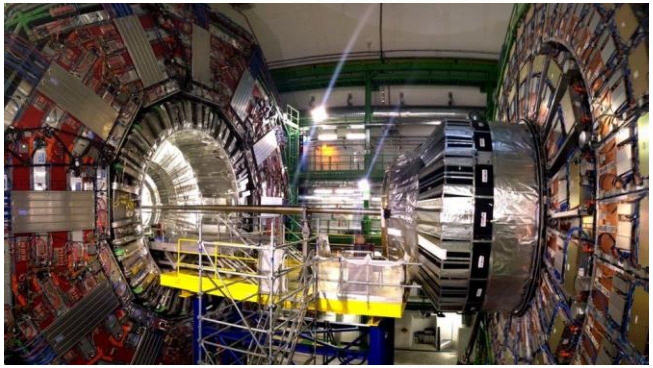
- Easier installation, easier access
- Less space restrictions
- Larger flexibility
  - Large momentum range
  - Flexible particle types

But only fraction of beam energy available for physics:

$$E_{CM} \approx \sqrt{(2\, m_0\, E_{beam})}$$

Collider

- All beam energy available for producing new particles/physics
- $E_{CM} \approx 2\, E_{beam}$



Physics at FT and collider are both useful and needed

Purpose and Users

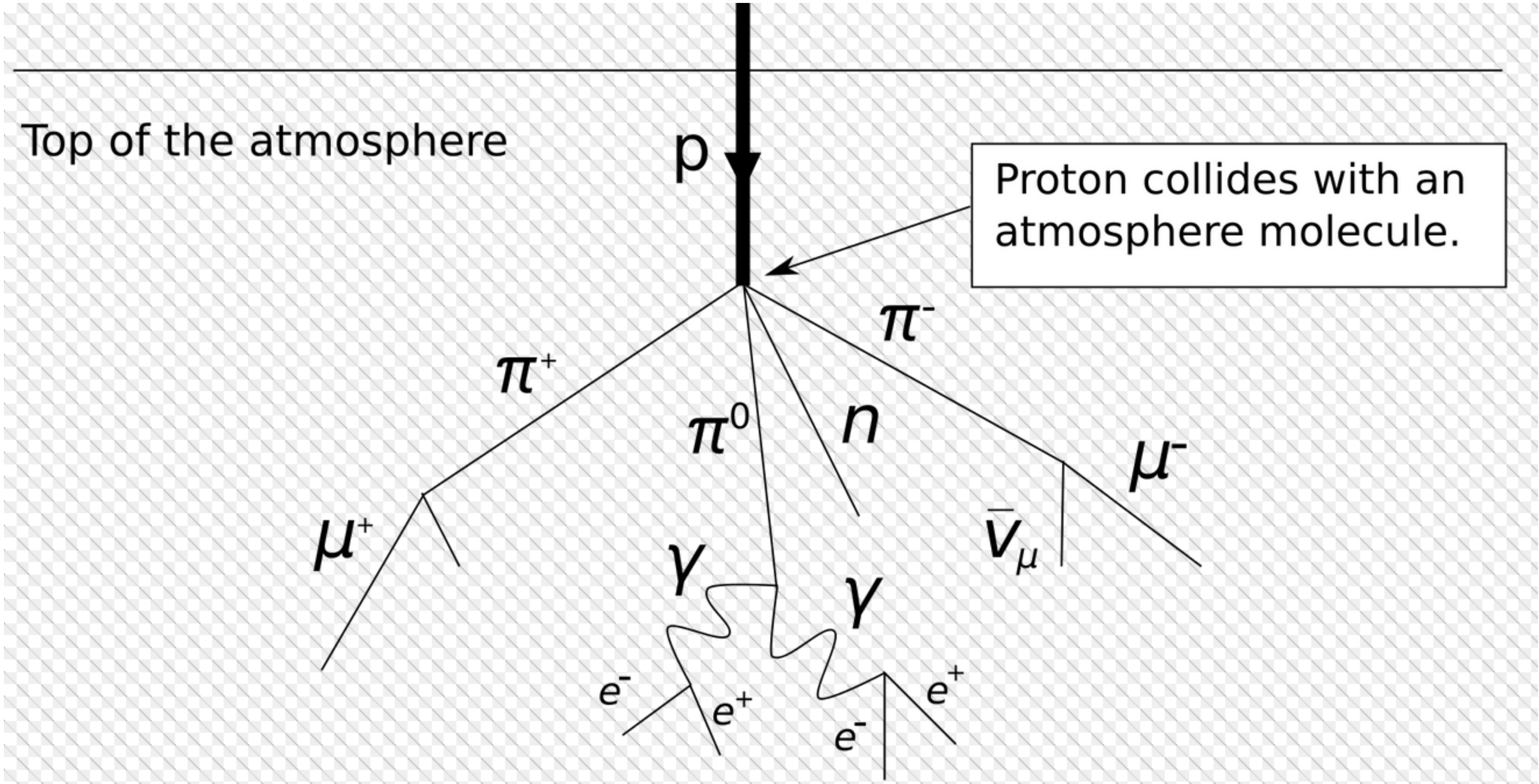
Secondary Beam Areas (SBA) are hosting:

- **FT experiments**: COMPASS,NA61, NA62, NA63, NA64, CLOUD, …
  - Precision studies (QCD, standard model, BSM physics)
  - Stable beam conditions for weeks and weeks
- **Radiation facilities**: HiRadMat, Charm, Irrad, GIF++
- **Test beams:**
  - Detector prototype tests
  - Detector calibration

    e.g. for LHC, linear colliders, space & balloon experiments
  - Outreach
  - Usually require a large spectrum of beam conditions within few days

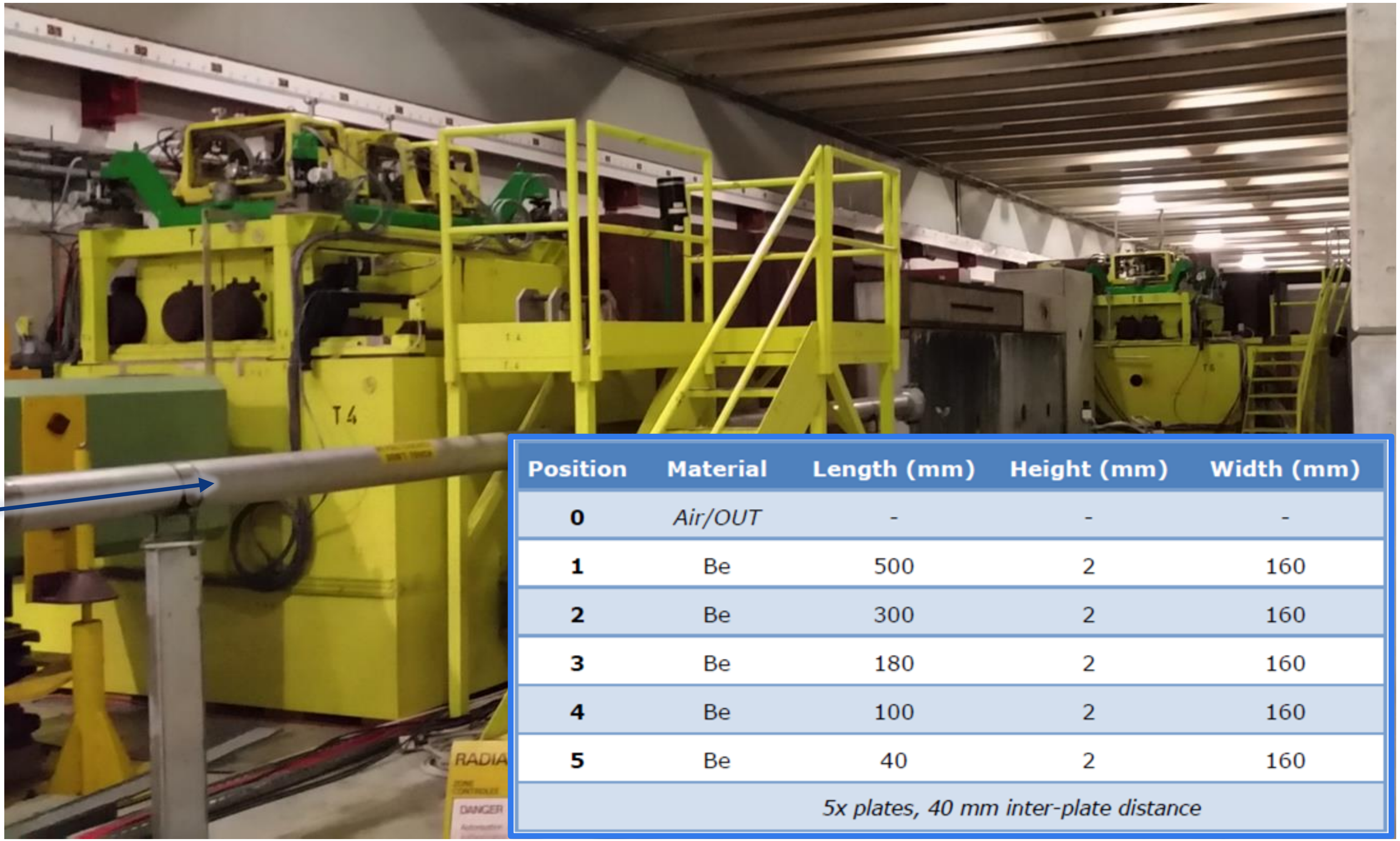
Targets and particle production

- Principle taken from cosmic radiation
  - Primary proton beam initiating hadronic cascade
  - Always followed by an electro-magnetic cascade



Targets and particle production

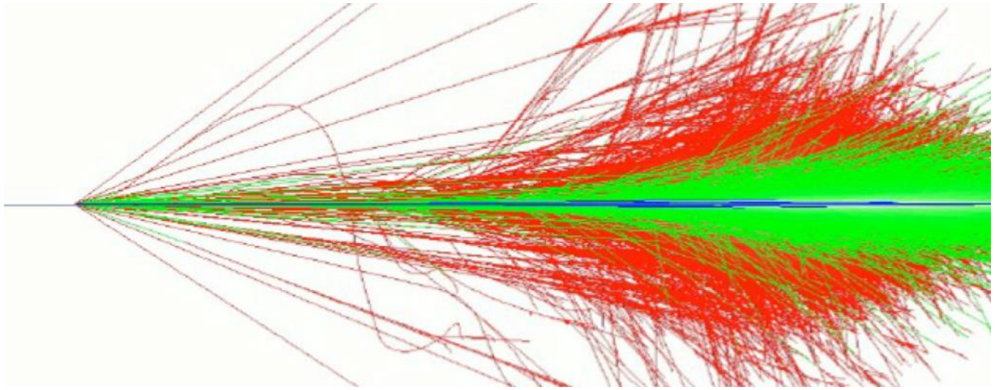
- Principle taken from cosmic radiation
- Particles are produced in a large momentum range



SPS beam

Position	Material	Length (mm)	Height (mm)	Width (mm)
0	*Air/OUT*	-	-	-
1	Be	500	2	160
2	Be	300	2	160
3	Be	180	2	160
4	Be	100	2	160
5	Be	40	2	160
5x plates, 40 mm inter-plate distance				

Target length and production rates

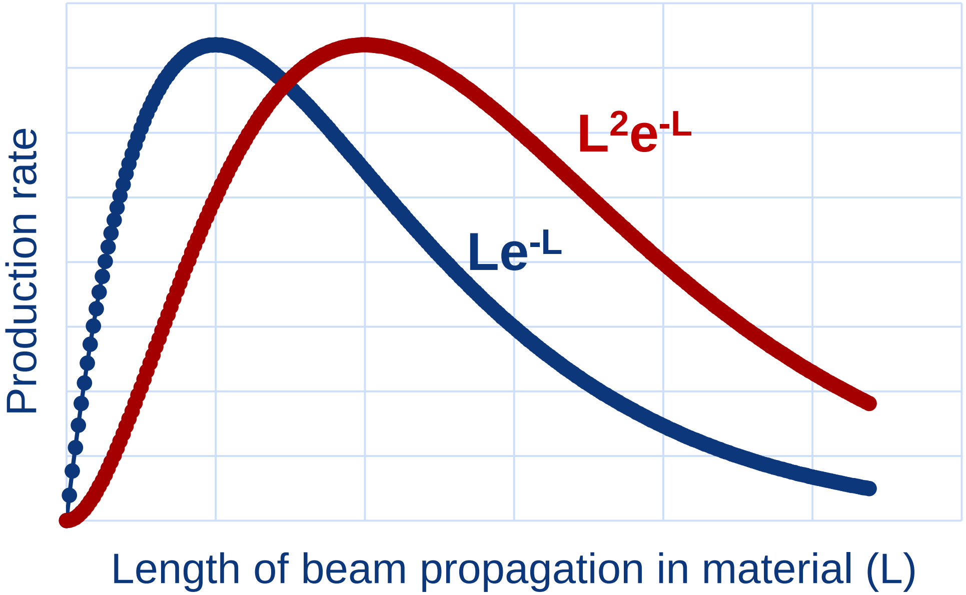


- Beryllium has
  - radiation length X_0 = 35.3 cm,
  - nuclear interaction length λ_I = 42.1 cm,

    => high X_0/λ_I ratio
  - low density (1.848 g/cm^3)
  - high melting point (1560 K)
- The e/π ratio increases approx. linearly with the target length
- Hadrons
  - are produced via p + N -> hadron (rate ~ L)
  - reabsorbed (rate ~ e^{-L})

  => Overall rate ~ Le^{-L} (maximum at $L \approx \lambda_I$)
- Electrons are mainly produced via
  - p + N -> π^0 -> γ γ (rate ~ L)
  - γ converts to $e^+ + e^-$ (rate also ~ L)
  - reabsorbed (rate ~ e^{-L})

  => Overall rate ~ $L^2 e^{-L}$ (maximum at $L \approx 2\lambda_I$)



Targets and hadron production

Atherton parameterisation (CERN 80-07):

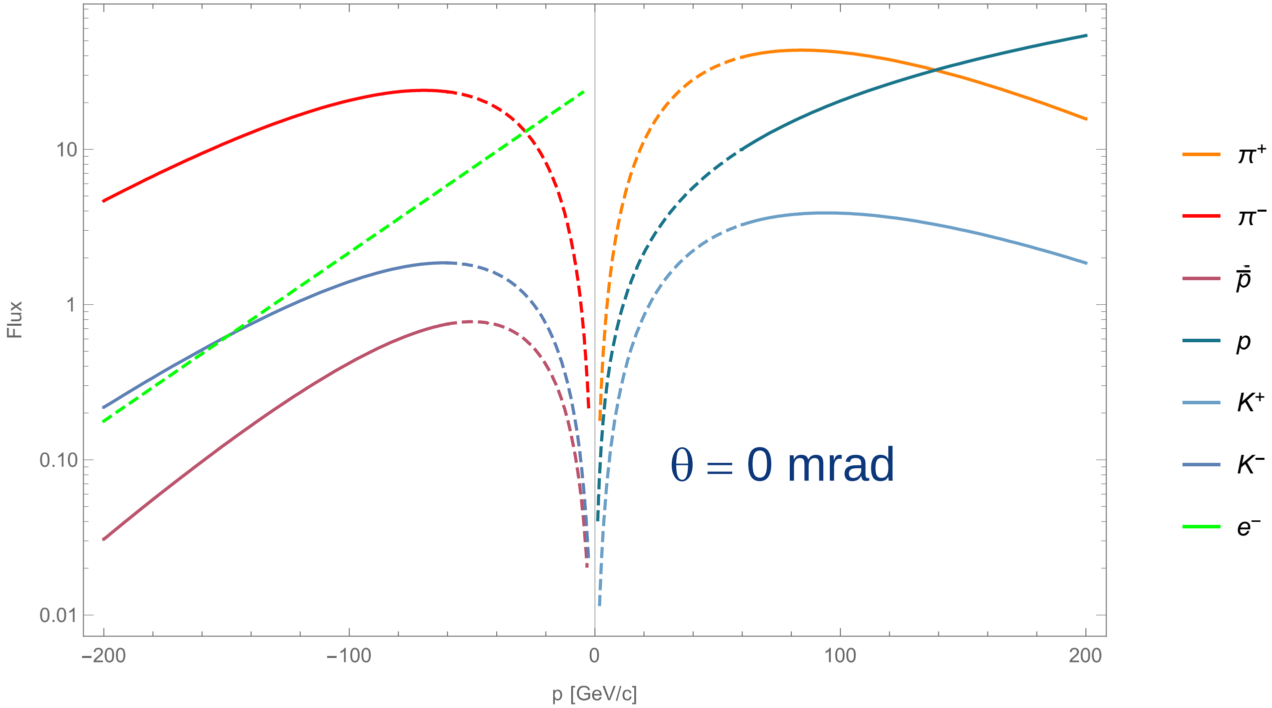
$$\frac{d^2N}{dp\,d\Omega} = A\left[\frac{B}{p_0} e^{-Bp/p_0}\right]\left[\frac{2Cp^2}{2\pi} e^{-C(p\theta)^2}\right]$$

$$\frac{d^2N}{dp\,d\Omega} = A\left[\frac{(B+1)}{p_0}\left(\frac{p}{p_0}\right)^B\right]\left[\frac{2Cp^2}{2\pi} e^{-C(p\theta)^2}\right]$$

with primary momentum p_0 and production angle θ

Flux per solid angle [steradian], per interacting proton, and per dp [GeV/c]

	A	B	C
p	0.8	-0.6	3.5



	A	B	C
π^+	1.2	9.5	5.0
π^-	0.8	11.5	5.0
K^+	0.16	8.5	3.0
K^-	0.10	13.0	3.5
$\bar{p}$	0.06	16.0	3.0

Note: Valid for primary interactions only! Extrapolation for momenta below 60 GeV/c

Targets and particle production

		Name		Q	Mass	Mean life (τ)	$c\tau$	Mean decay distance	Decays
					[MeV/c²]	[s]	[m]	[m/GeV/c]	
Leptons		**Electron**	**e**	±e	0.511	stable			
		Muon	**μ**	±e	105.6	2.2×10^{-6}	659.6	6.3×10^{3}	$\mu^+ \longrightarrow e^+ \bar{\nu}_e \nu_\mu$ (100%)
Hadrons	Mesons	**Pion**	**π**	±e	139.6	2.6×10^{-8}	7.8	56.4	$\pi^+ \longrightarrow \mu^+ \nu_\mu$ (100%)
		Kaon	**K**	±e	493.6	1.23×10^{-8}	3.7	8.38	$K^+ \longrightarrow \mu^+ \nu_\mu$ (63%) $\pi^0 e^+ \nu_e$ (5%) $\pi^0 \mu^+ \nu_\mu$ (3%) $\pi^+ \pi^0$ (...) (28.9%)
			K^0	0	497.6	**K^0_S** 8.9×10^{-11}	0.02	0.060	$K^0_S \longrightarrow \pi^0 \pi^0$ (30.7%) $\pi^+\pi^-$ (69.2%)
						K^0_L 5.12×10^{-8}	15.34	34.4	$K^0_L \longrightarrow \pi^\pm e^\mp \nu_e$ (40.5%) $\pi^\pm \mu^\mp \nu_\mu$ (27.0%) $3\pi^0$ (19.5%) $\pi^+\pi^-\pi^0$ (12.5%)
	Baryons	**Proton**	**p**	±e	938	stable			
		Lambda	**Λ**	0	1115.6	2.63×10^{-10}	0.079	0.237*	$\Lambda^0 \longrightarrow p\, \pi^-$ (63.9%)
		Sigma Hyperons	**Σ^+**	+e	1189.3	8.02×10^{-11}	0.024	0.068*	$\Sigma^+ \longrightarrow p\, \pi^0$ (51.57%)
			Σ^-	-e	1197.4	1.48×10^{-10}	0.044	0.125*	$\Sigma^- \longrightarrow n\, \pi^-$ (99.84%)

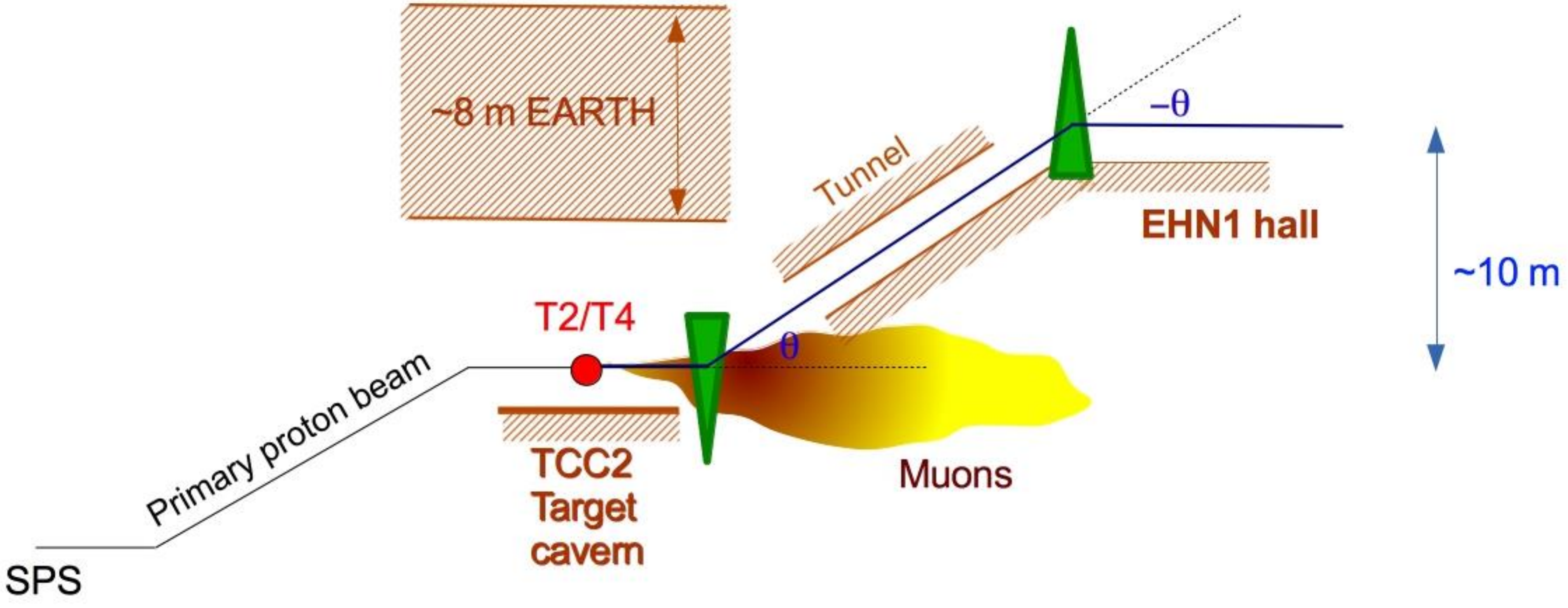
(*) for 10 GeV/c

Beamlines

- Experiments and test beams require “clean” beams with high purity (one particle type) and small momentum spread
- Beam lines design (“optics”)
  1. Collect produced particles from target
  2. Select momentum
  3. Select particle type
  4. Transport beam to experiment
  5. Select beam spot size for experiment

NA beamline design considerations

- NA beams were originally (end of 1970's) designed for the fixed target experiments. Design considerations were
  - Muon range (absorb underground)
  - Charged pion lifetime
  - Momentum selection ($2 \cdot 10^{-4}$)



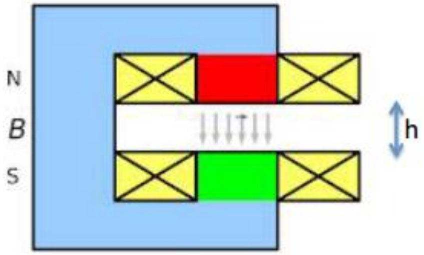
Dipoles

Basic beam design

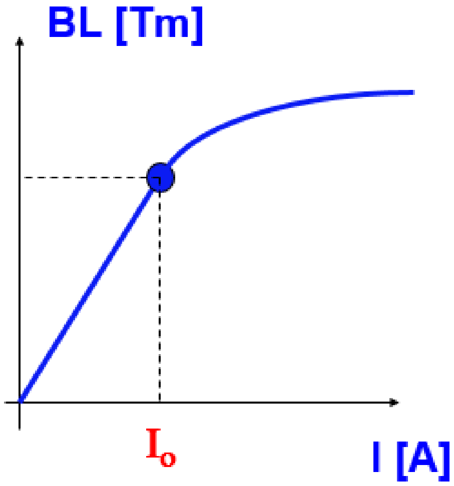
- Transport and momentum (p) selection: bending magnets

Dipole electro-magnets:

$$\boxed{\vec{F} = q \cdot \vec{v} \times \vec{B}}$$



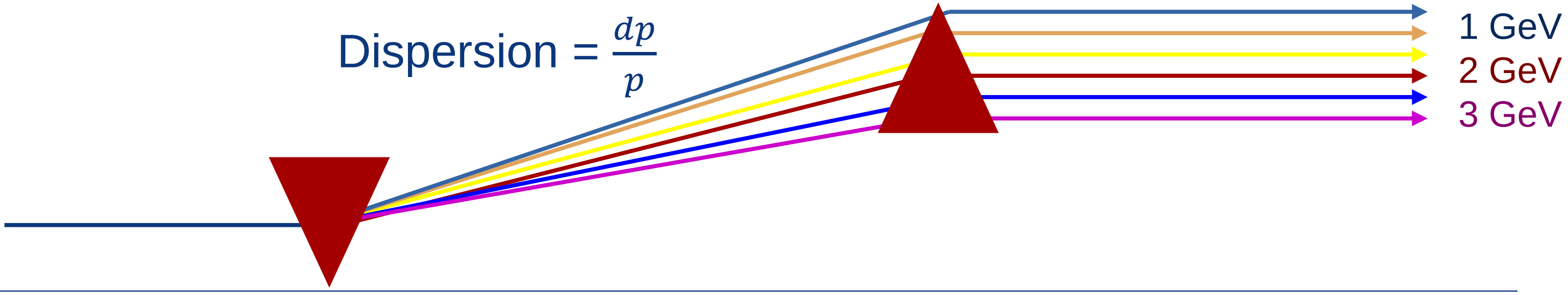
$$B = \frac{\mu_0 n I}{h}$$



$$\theta\,[mrad] = \frac{299.79 Bl\ [T \cdot m]}{p[GeV]}$$

For example:

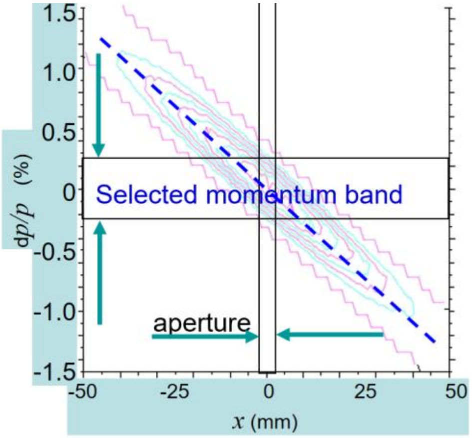
$$\text{Dispersion} = \frac{dp}{p}$$

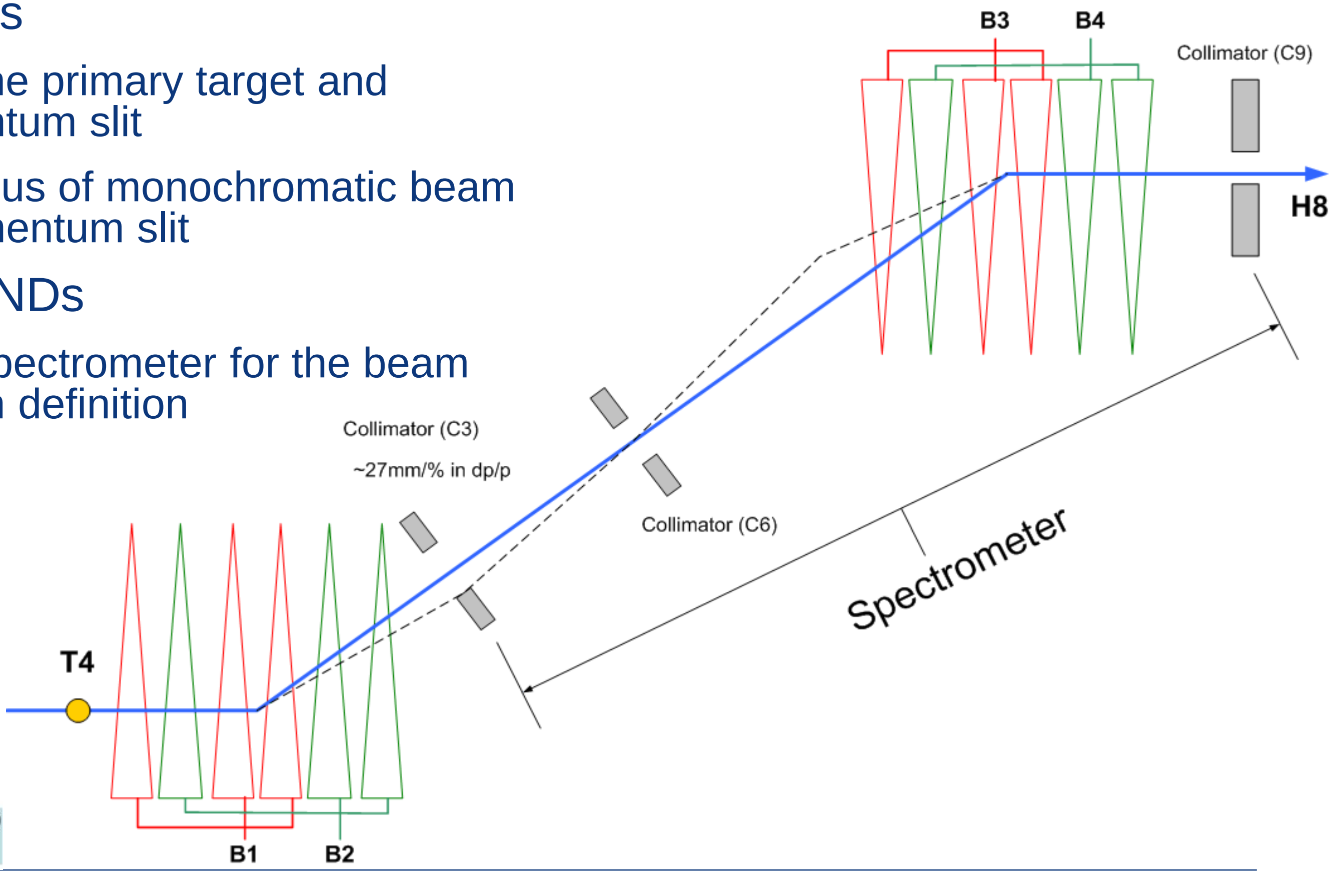


Momentum selection

Basic beam design

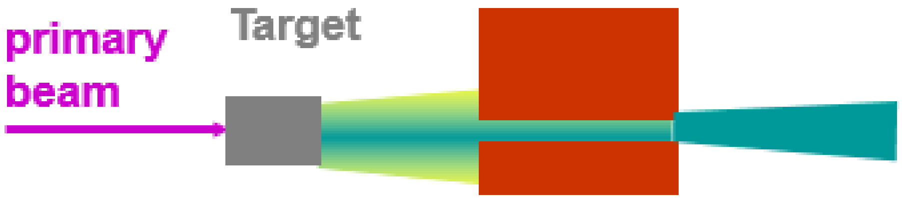
- momentum selection in the vertical plane
- two sets of bending magnets
  - Upstream BENDs
    - Between the primary target and the momentum slit
    - Vertical focus of monochromatic beam at the momentum slit
  - Downstream BENDs
    - the main spectrometer for the beam momentum definition





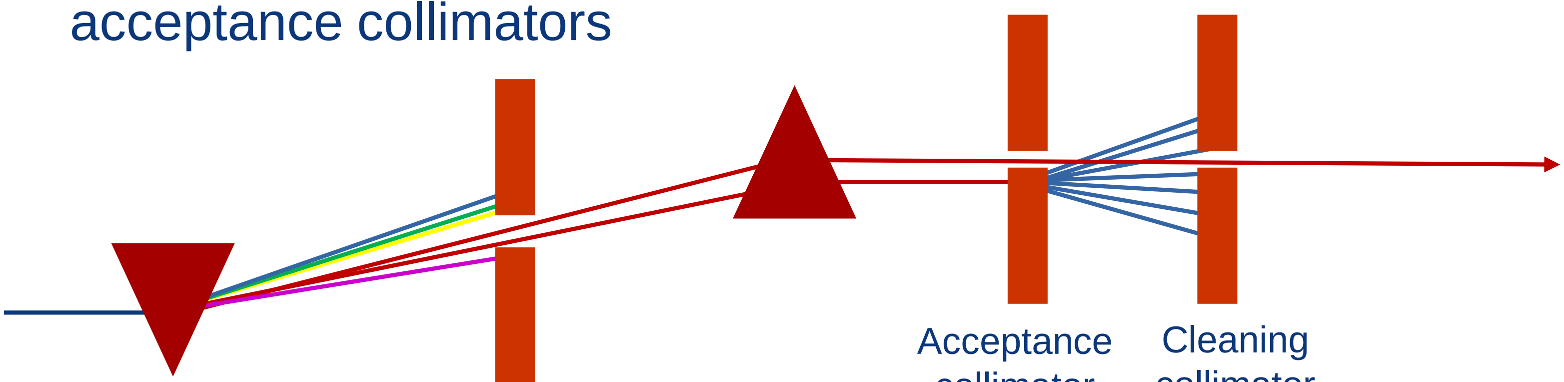
Secondary beamlines - collimators

- TAX (Target attenuator)
  - Define initial acceptance of the beam line

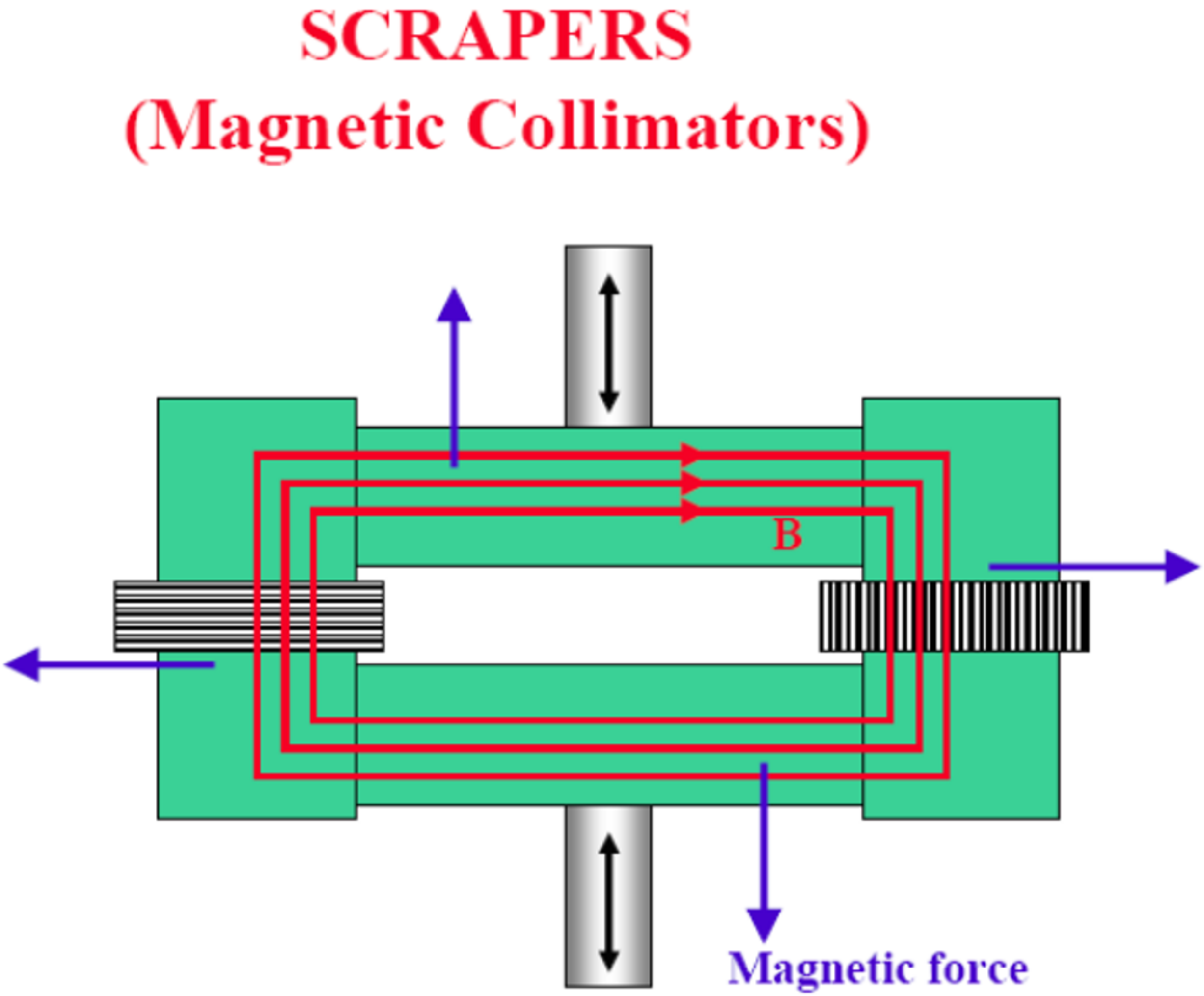


Acceptance predefined by TAX

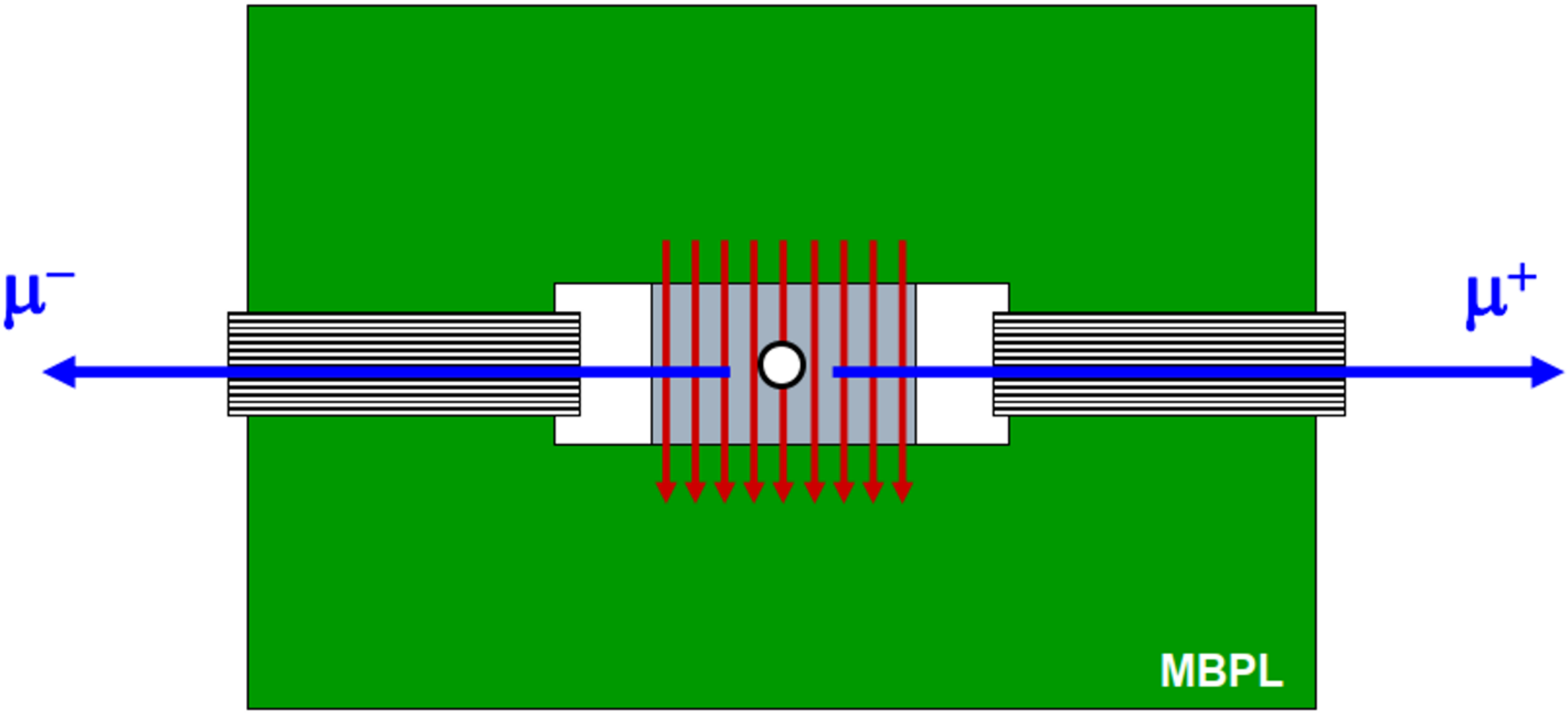
- Acceptance collimators
- Cleaning collimators
  - Absorb secondary particles produced on the jaws of acceptance collimators



Secondary beamlines – muon sweepers



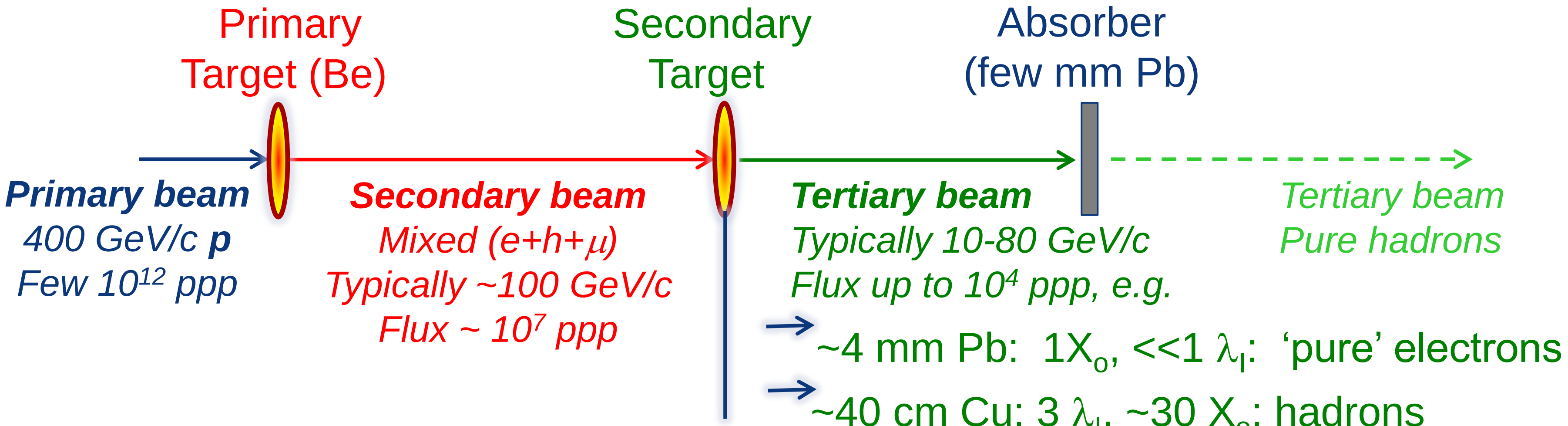
Secondary beamlines – muon sweepers



Secondary beamlines - intensities

Basic beam design

- Selection of particle types



Primary Target (Be)

Secondary Target

Absorber (few mm Pb)

Primary beam
*400 GeV/c **p***
Few 10^{12} ppp

Secondary beam
Mixed (e+h+μ)
Typically ~100 GeV/c
Flux ~ 10^7 ppp

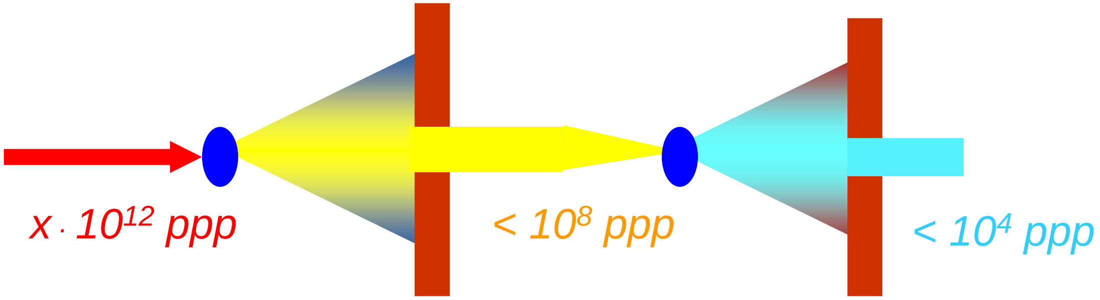
Tertiary beam
Typically 10-80 GeV/c
Flux up to 10^4 ppp, e.g.

→ ~4 mm Pb: $1X_o$, $<<1\ \lambda_I$: ‘pure’ electrons

→ ~40 cm Cu: $3\ \lambda_I$, $\sim 30\ X_o$: hadrons

Tertiary beam
Pure hadrons

- Intensities

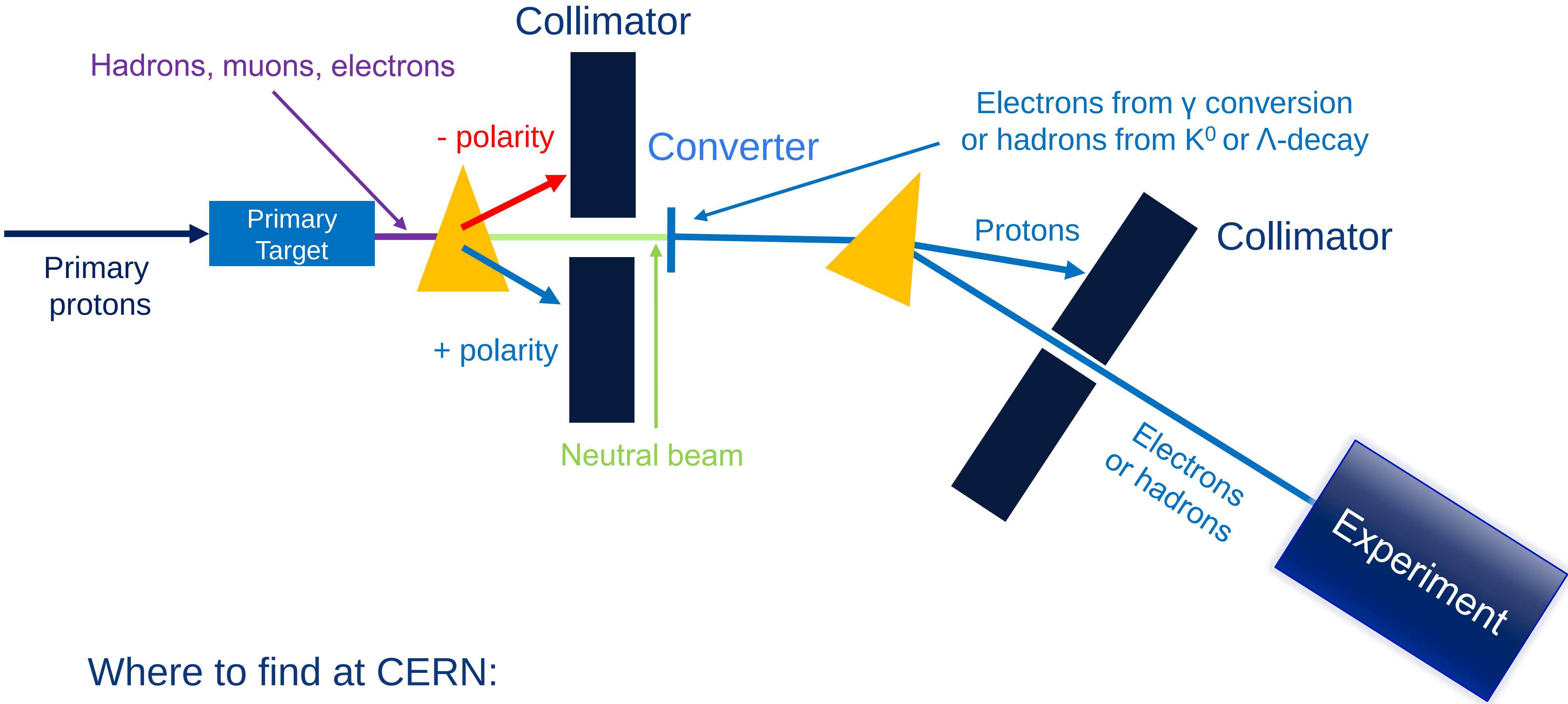


$x \cdot 10^{12}$ ppp

$< 10^8$ ppp

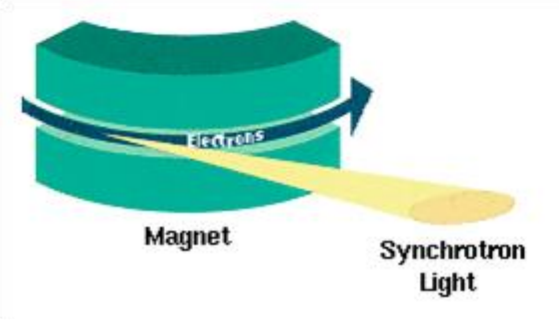
$< 10^4$ ppp

Selection of particle type - Converter



Where to find at CERN:
North Area: H2, H4
East Area: T9 (starting 2021)

Selection of particle type - Synch. rad.



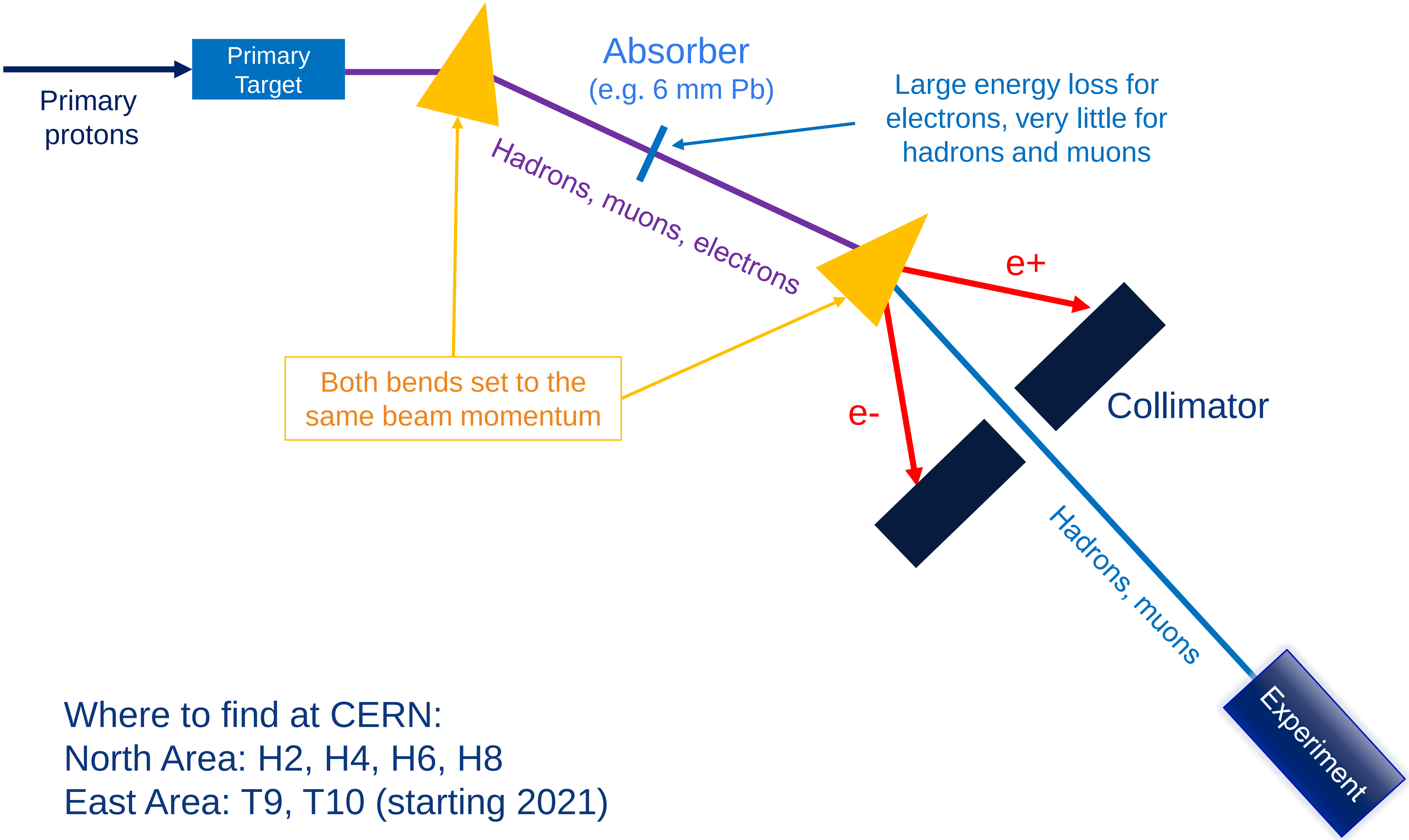
- Synchrotron radiation

(for one full revolution)

$$P_s = \frac{e^2 c}{6\pi\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2}$$

- E.g. $e^{\pm}$ at 200 GeV lose in 1° bending magnet of 1 T field 590 MeV
  - => With beamline momentum acceptance of $\Delta p/p < 0.3$ % it is possible to separate them from (heavier) hadrons and muons. So set up the following bends either
    - at the constant energy to select heavier particles or
    - scale it with energy loss of electrons.
    - Works only for $p_e > 120$-150 GeV/c

Selection of particle type - Absorber

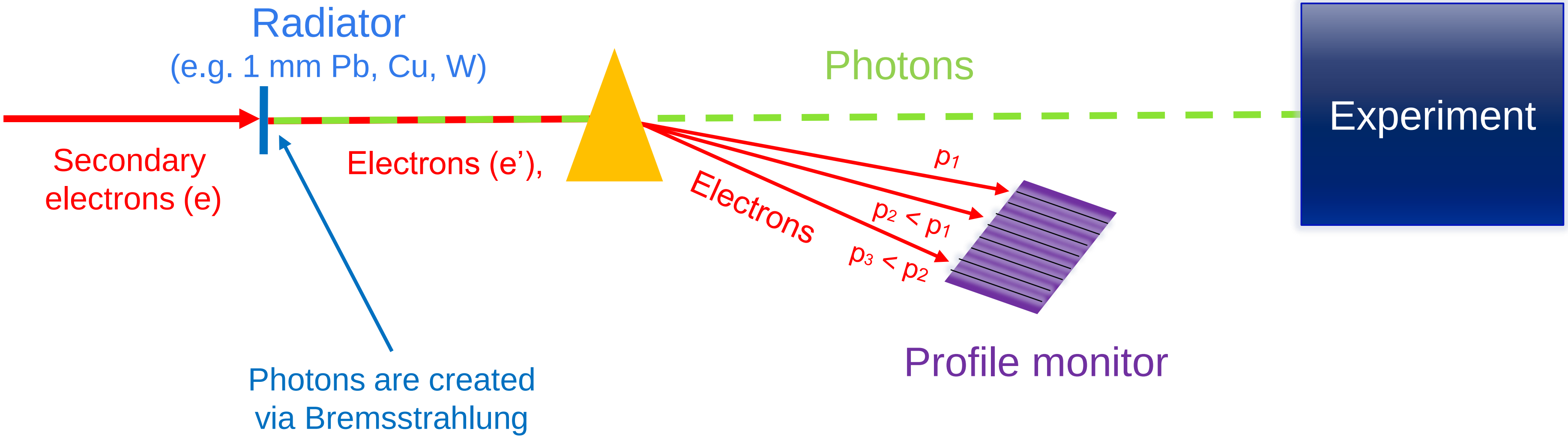


Large energy loss for electrons, very little for hadrons and muons

Both bends set to the same beam momentum

Where to find at CERN:
North Area: H2, H4, H6, H8
East Area: T9, T10 (starting 2021)

Selection of particle type - Radiator



- Time resolution - electron by electron
- Transverse position gives information on e- momentum
- $p_\gamma = p_e - p_{e'}$
- Result : tagged photon beam

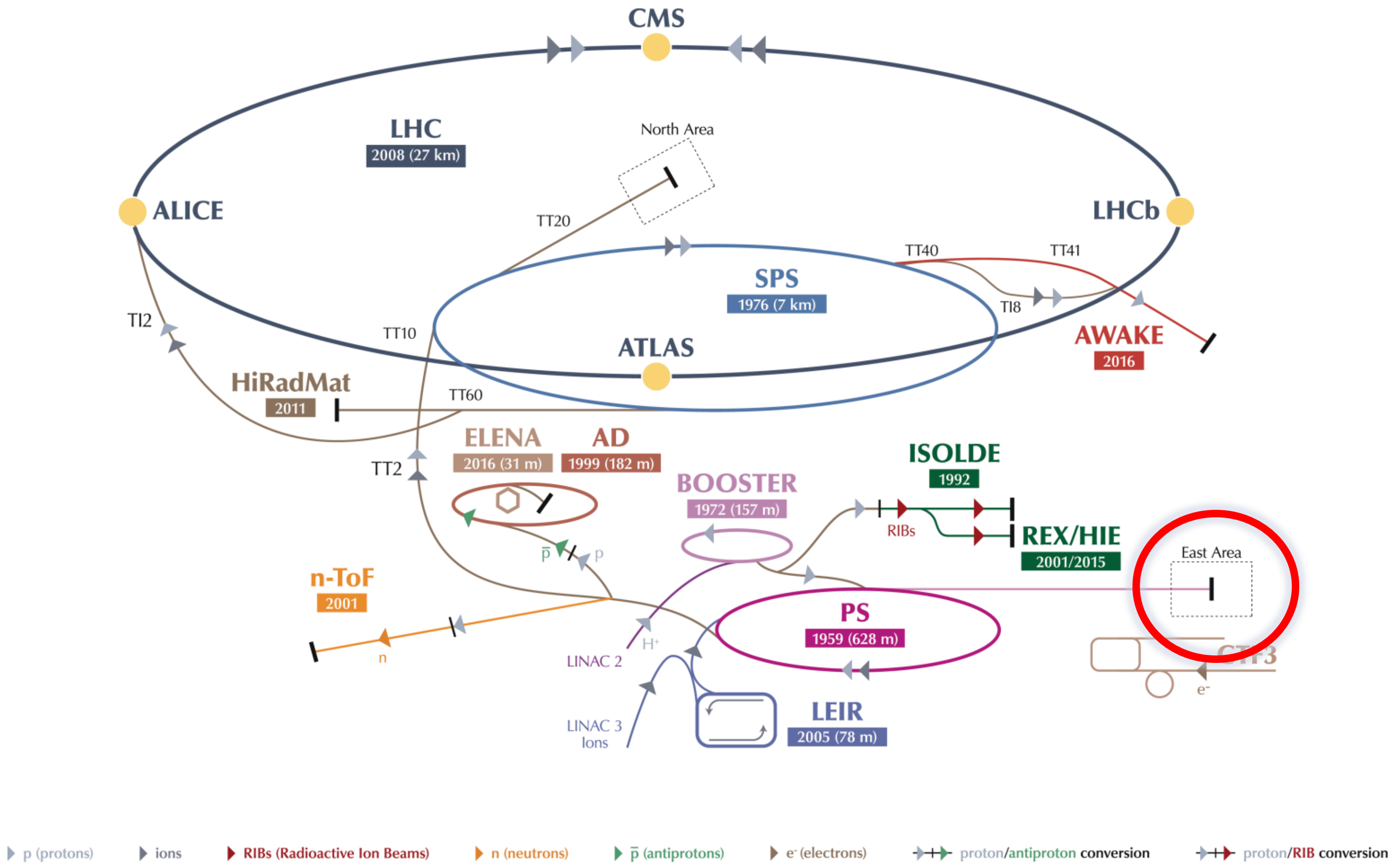
Where to find at CERN:

(Ad hoc installation, but usually used at)

North Area: H2, H4

East Area: T9

Beams from PS



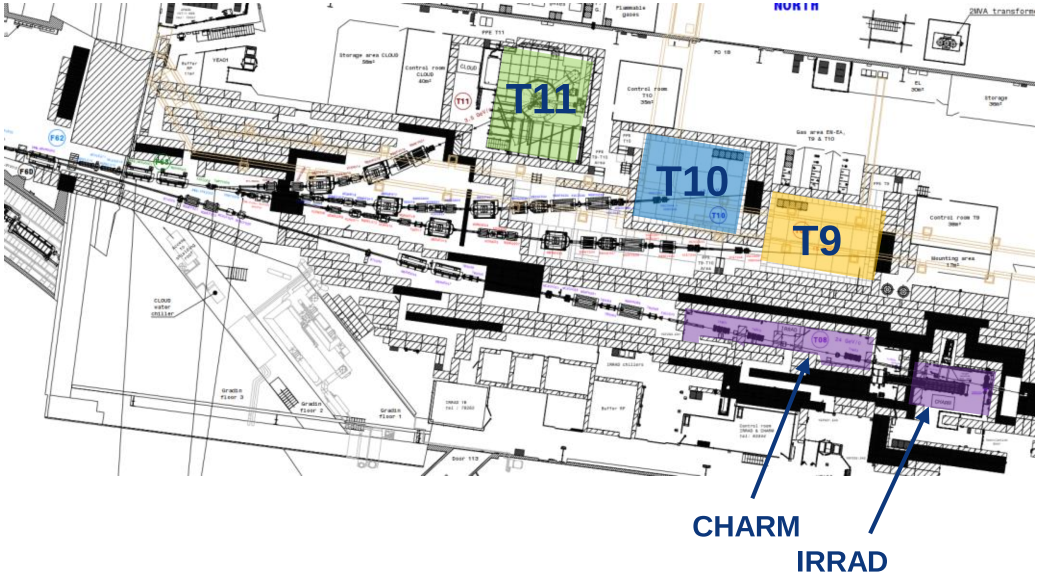
LHC Large Hadron Collider **SPS** Super Proton Synchrotron **PS** Proton Synchrotron **AD** Antiproton Decelerator **CTF3** Clic Test Facility

AWAKE Advanced WAKefield Experiment **ISOLDE** Isotope Separator OnLine **REX/HIE** Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring **LINAC** LINear ACcelerator **n-ToF** Neutrons Time Of Flight **HiRadMat** High-Radiation to Materials

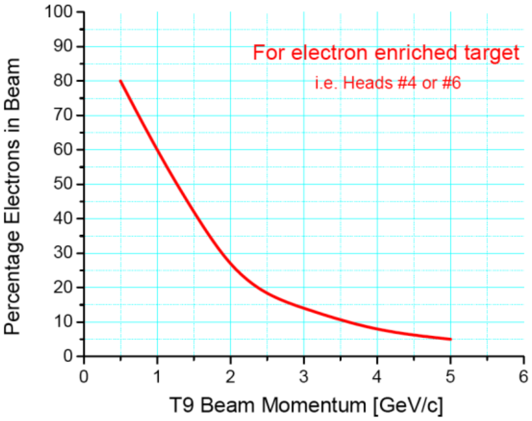
East Area

Area under renovation



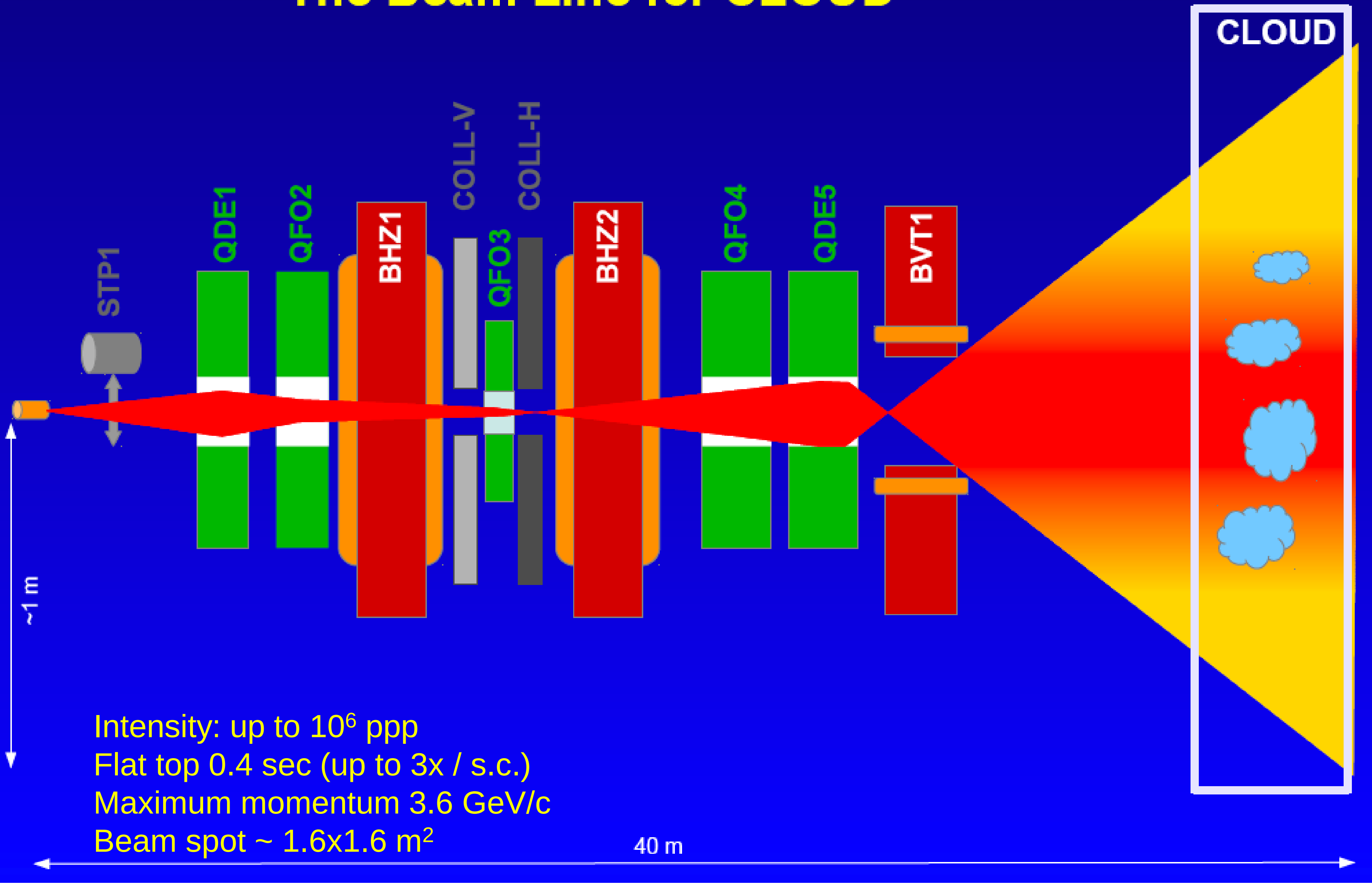
After LS2

- Secondary beams:
  - Momentum < 15 GeV/c
  - Irradiation facilities CHARM and IRRAD
  - Test beamlines T9 and T10
  - T11 beamline for CLOUD experiment
  - Horizontal momentum selection
- Particle types and intensity
  - Pure electrons, hadrons, muons
  - Max. $\sim 5\cdot 10^6$ particles per spill
- Spill structure from PS
  - 400ms spill length
  - Typically 1 spill every 18s (15bp), more on request
- Quick access from control room to experimental area (< 1 minute)
- Short cables



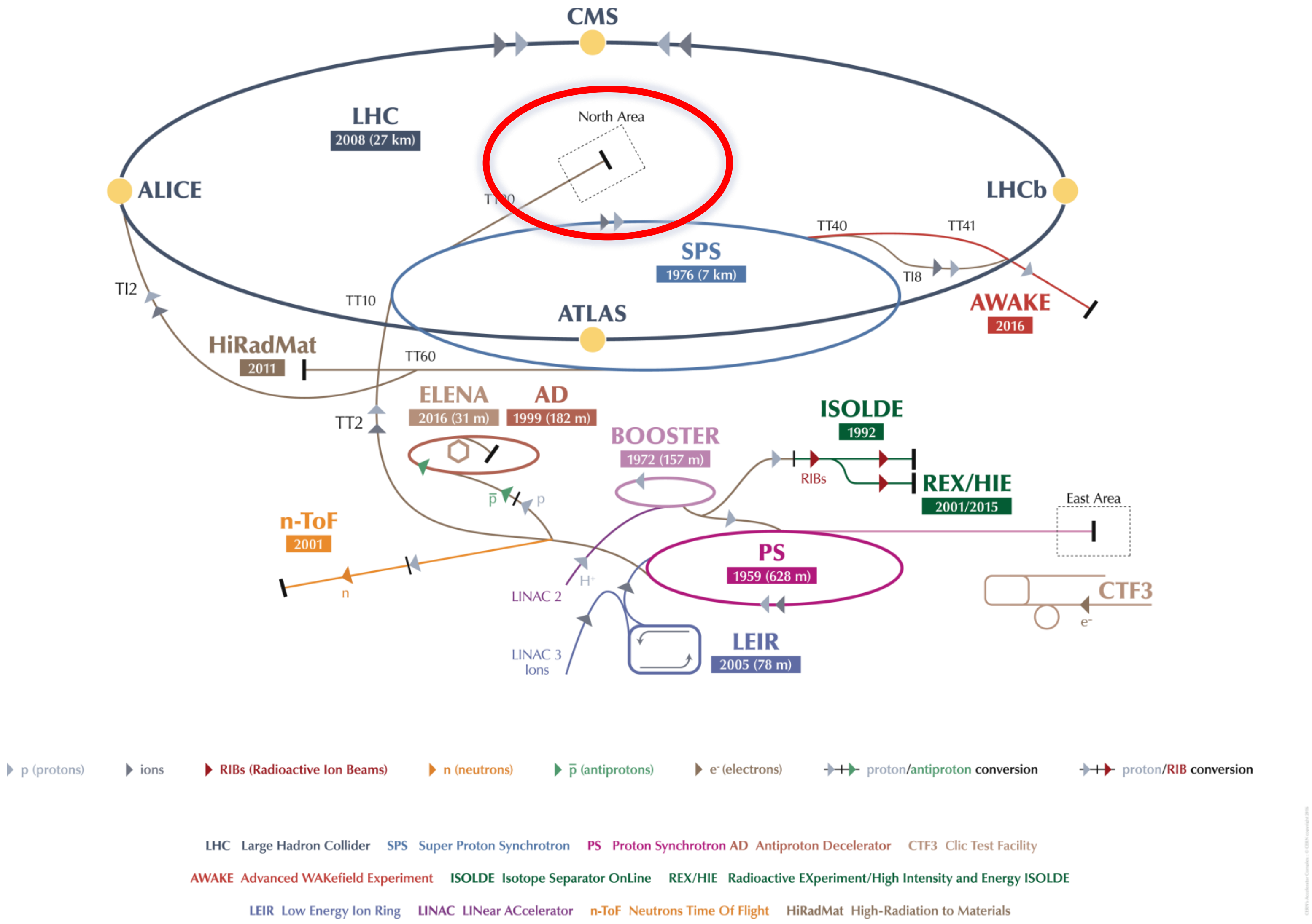
The CLOUD Experiment in T11 Beam

The Beam Line for CLOUD

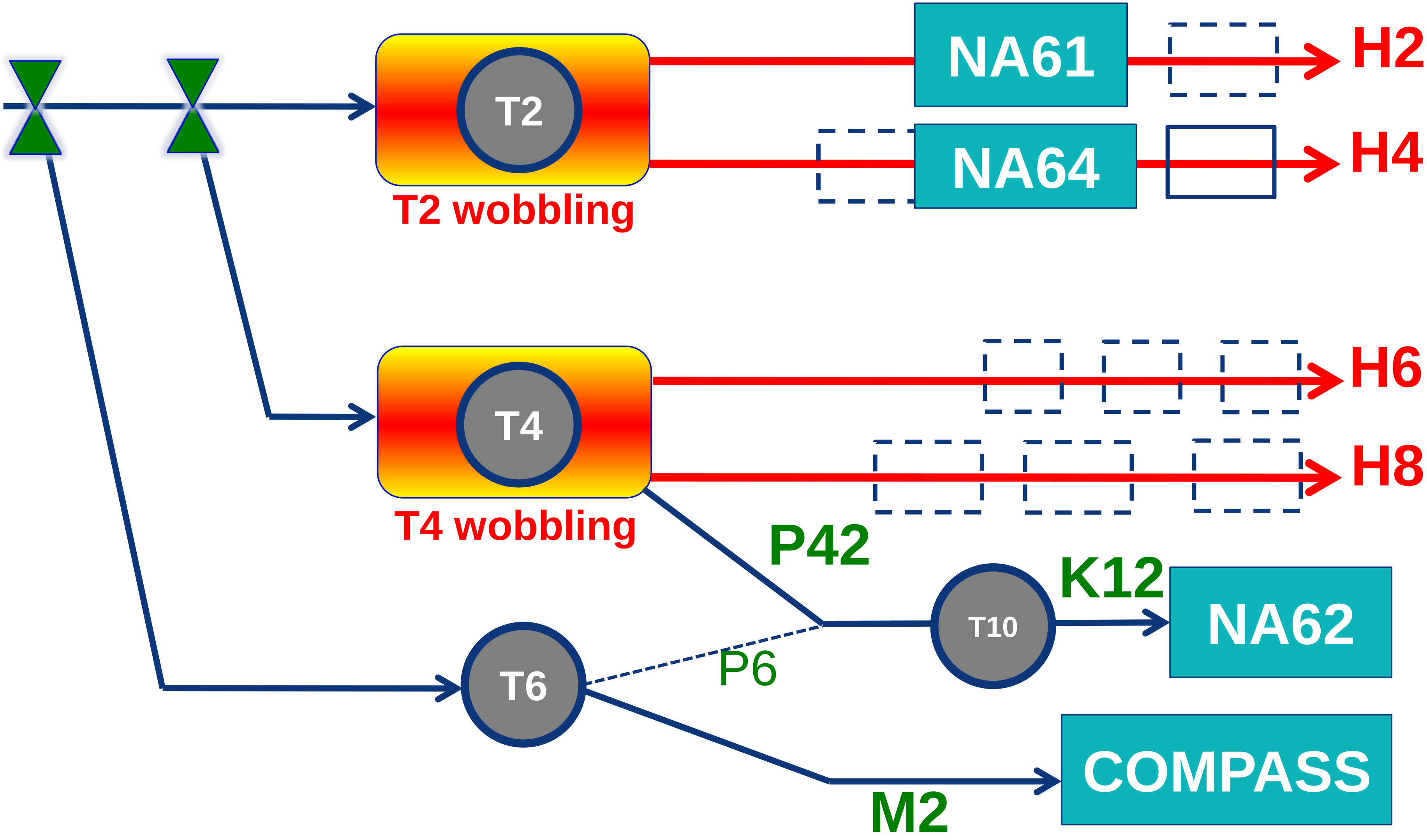


Intensity: up to 10^6 ppp
Flat top 0.4 sec (up to 3x / s.c.)
Maximum momentum 3.6 GeV/c
Beam spot ~ 1.6x1.6 m^2

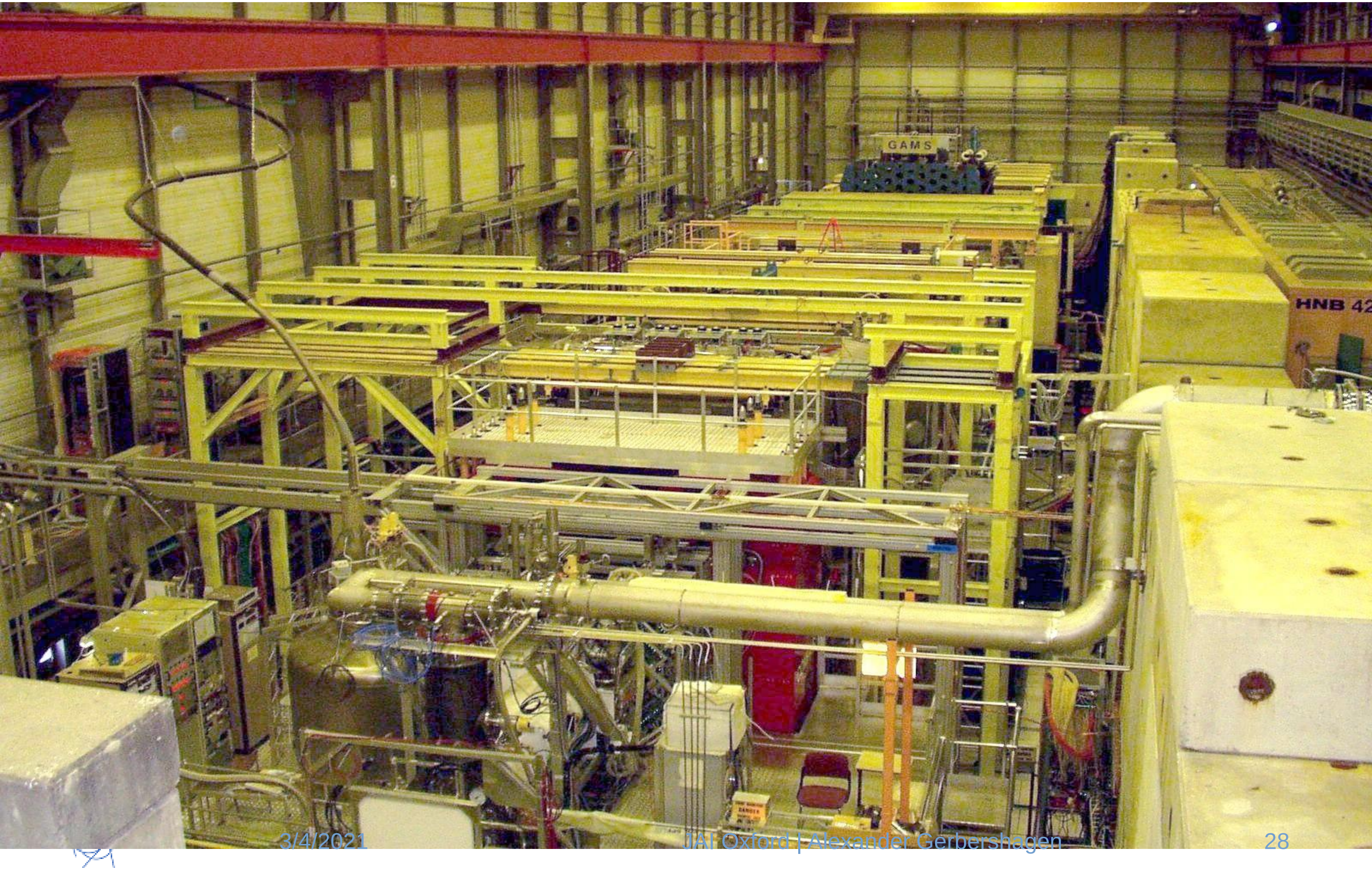
Beams from SPS



North Area beamlines - schematic

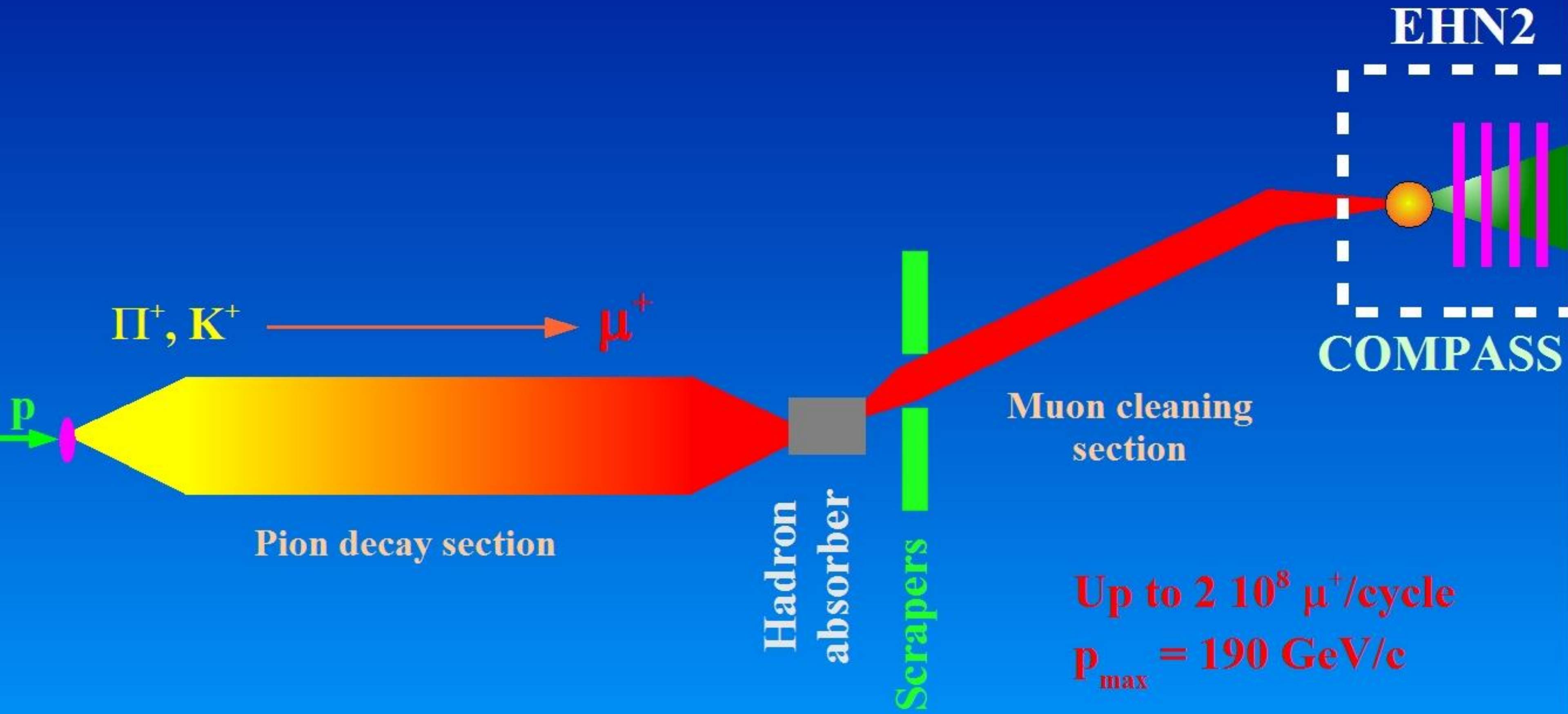


EHN2: COMPASS



THE M2 MUON BEAM

FOR COMPASS / NA58



Up to 2 10^8 μ^+/cycle

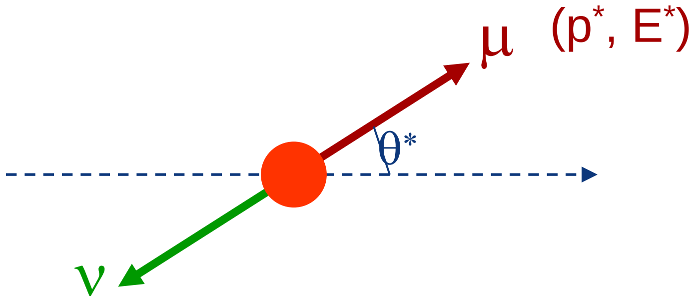
p_{max} = 190 GeV/c

Muons from pion decay

- Pion decay in π center of mass:

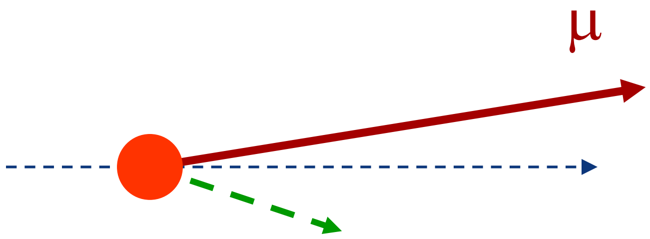
$$p^* = \frac{m_\pi^2 - m_\mu^2}{2\, m_\pi} = 30 \text{ MeV/c}$$

$$E^* = \frac{m_\pi^2 + m_\mu^2}{2\, m_\pi} = 110 \text{ MeV}$$



- Boost to laboratory frame:

$$E_\mu = \gamma_\pi \left(E^* + \beta_\pi\, p^* \cos\theta^*\right) \text{ with } \beta_\pi \approx 1$$



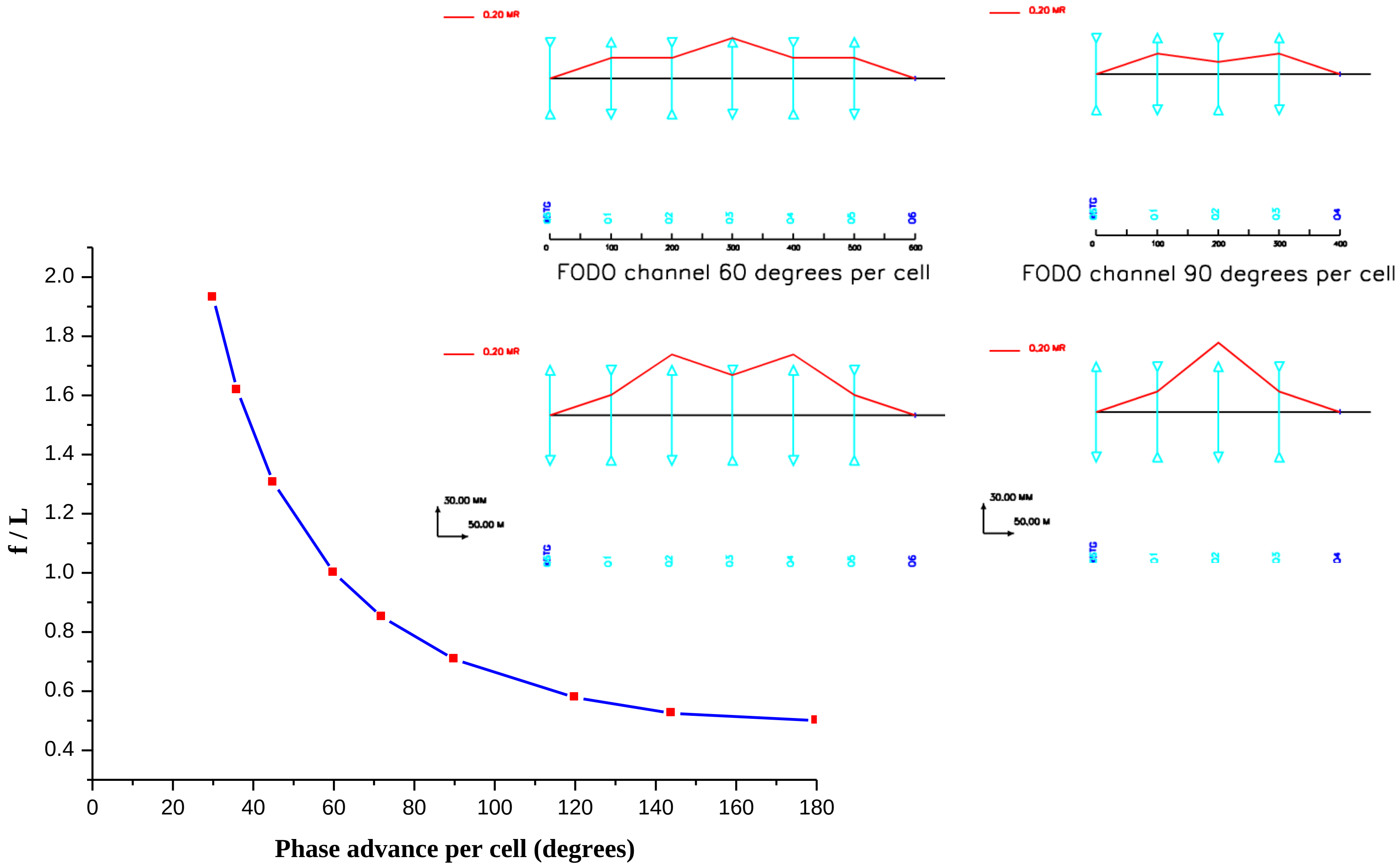
- Limiting cases:

$\cos\theta = +1 \rightarrow E_{max} = 1.0\, E_\pi$

$\cos\theta = -1 \rightarrow E_{min} = 0.57\, E_\pi$

$\Rightarrow$ $0.57 < E_\mu / E_\pi < 1$

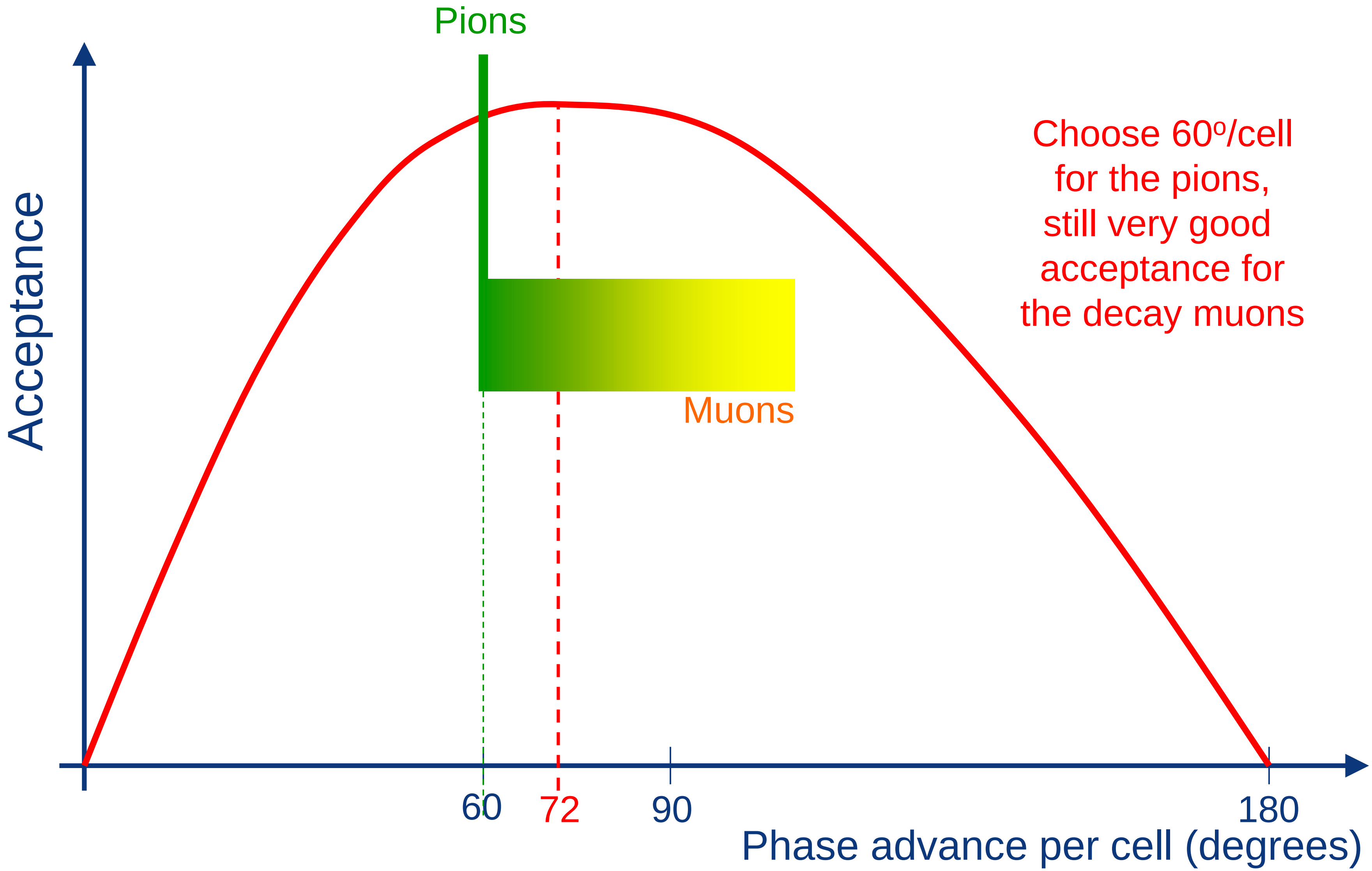
Momentum acceptance of FODO cells



FODO channel 60 degrees per cell

FODO channel 90 degrees per cell

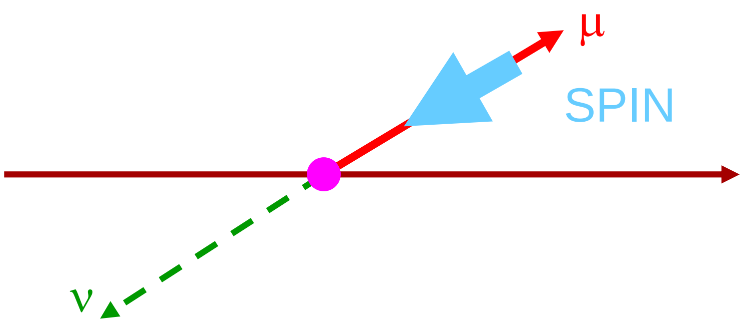
Phase advance for M2 beam

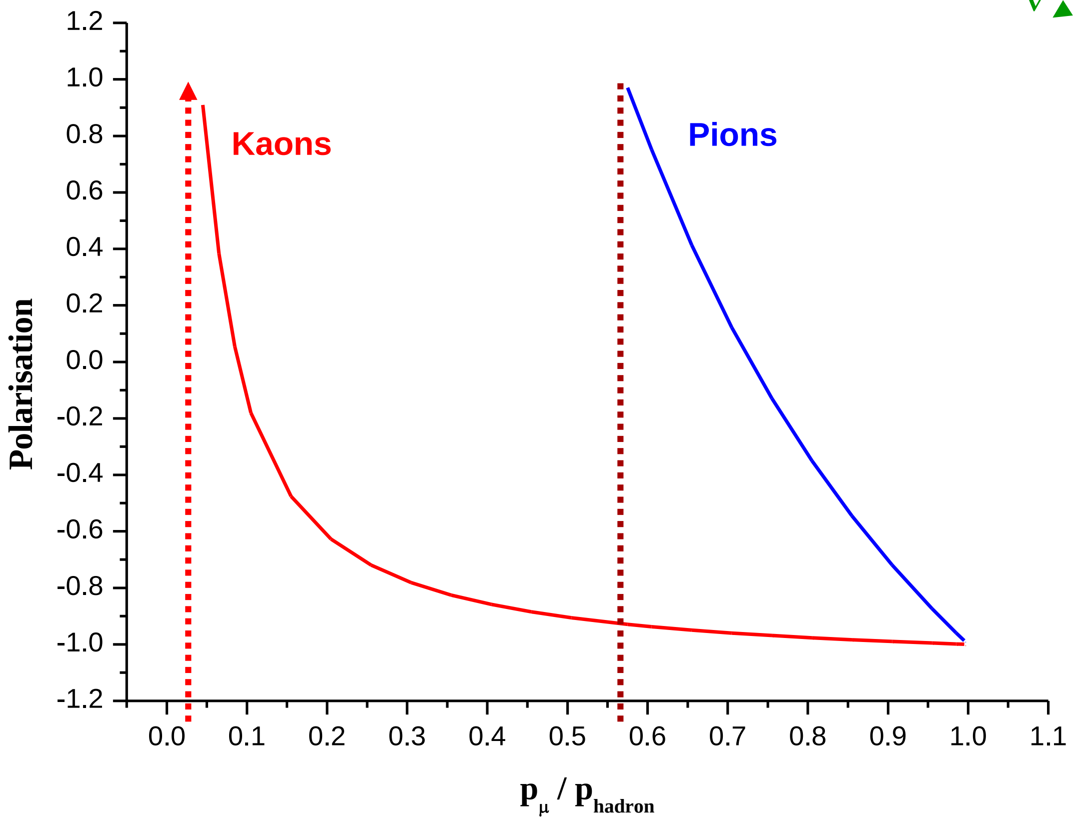


Choose 60º/cell
for the pions,
still very good
acceptance for
the decay muons

Muon Polarisation

Muons from pion decay are naturally polarised through Parity Violation:





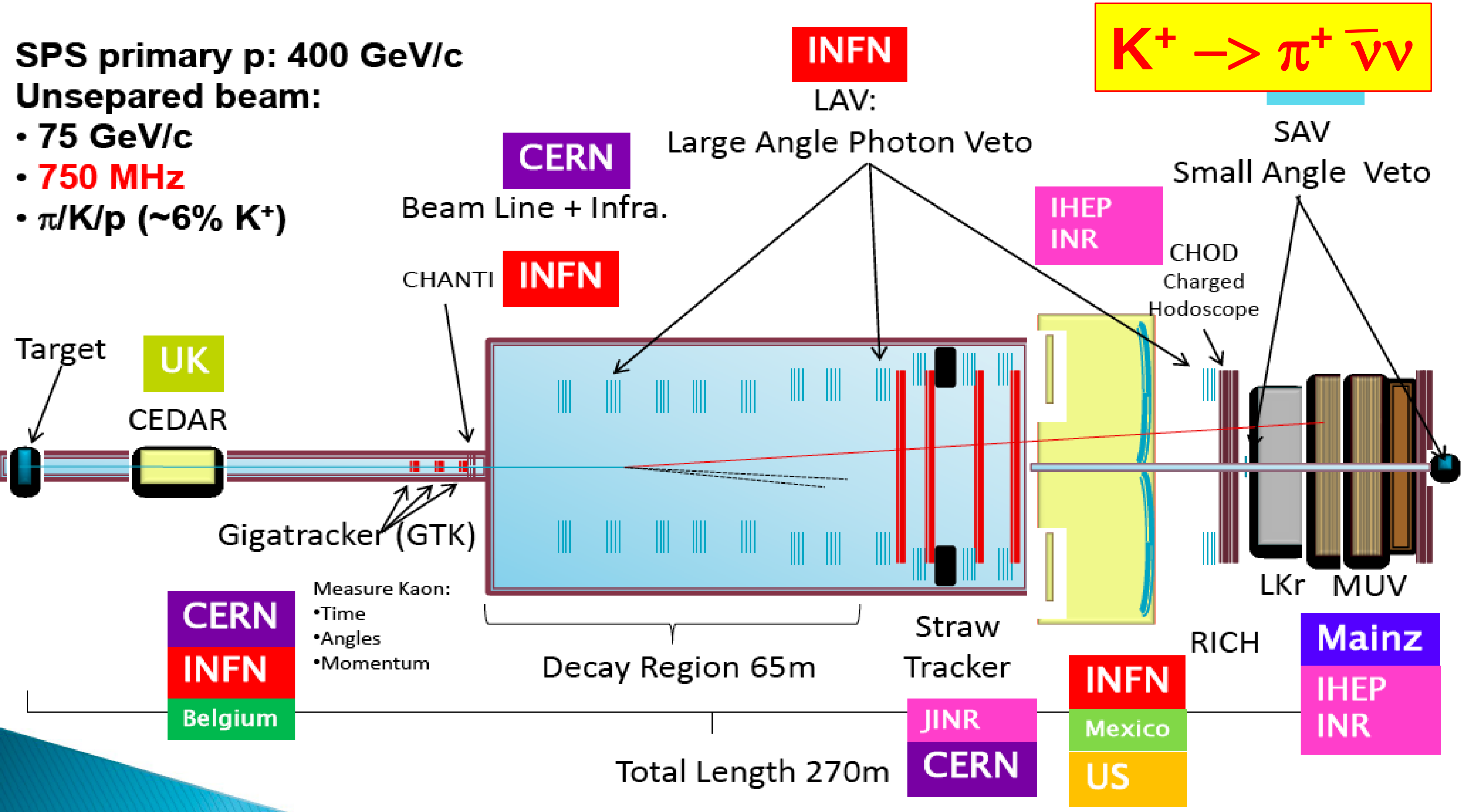
For the typical COMPASS conditions, p_μ / p_π = 0.92 and the measured muon polarisation is about -80%

NA62 Beam and Detectors

SPS primary p: 400 GeV/c
Unsepared beam:

- **75 GeV/c**
- **750 MHz**
- **π/K/p (~6% K^+)**

$K^+ \to \pi^+ \bar{\nu}\nu$



INFN
LAV:
Large Angle Photon Veto

CERN
Beam Line + Infra.

SAV
Small Angle Veto

IHEP
INR
CHOD
Charged
Hodoscope

CHANTI INFN

Target

UK
CEDAR

Gigatracker (GTK)

CERN
INFN
Belgium

Measure Kaon:
- Time
- Angles
- Momentum

Decay Region 65m

Straw
Tracker

JINR
CERN

RICH

INFN
Mexico
US

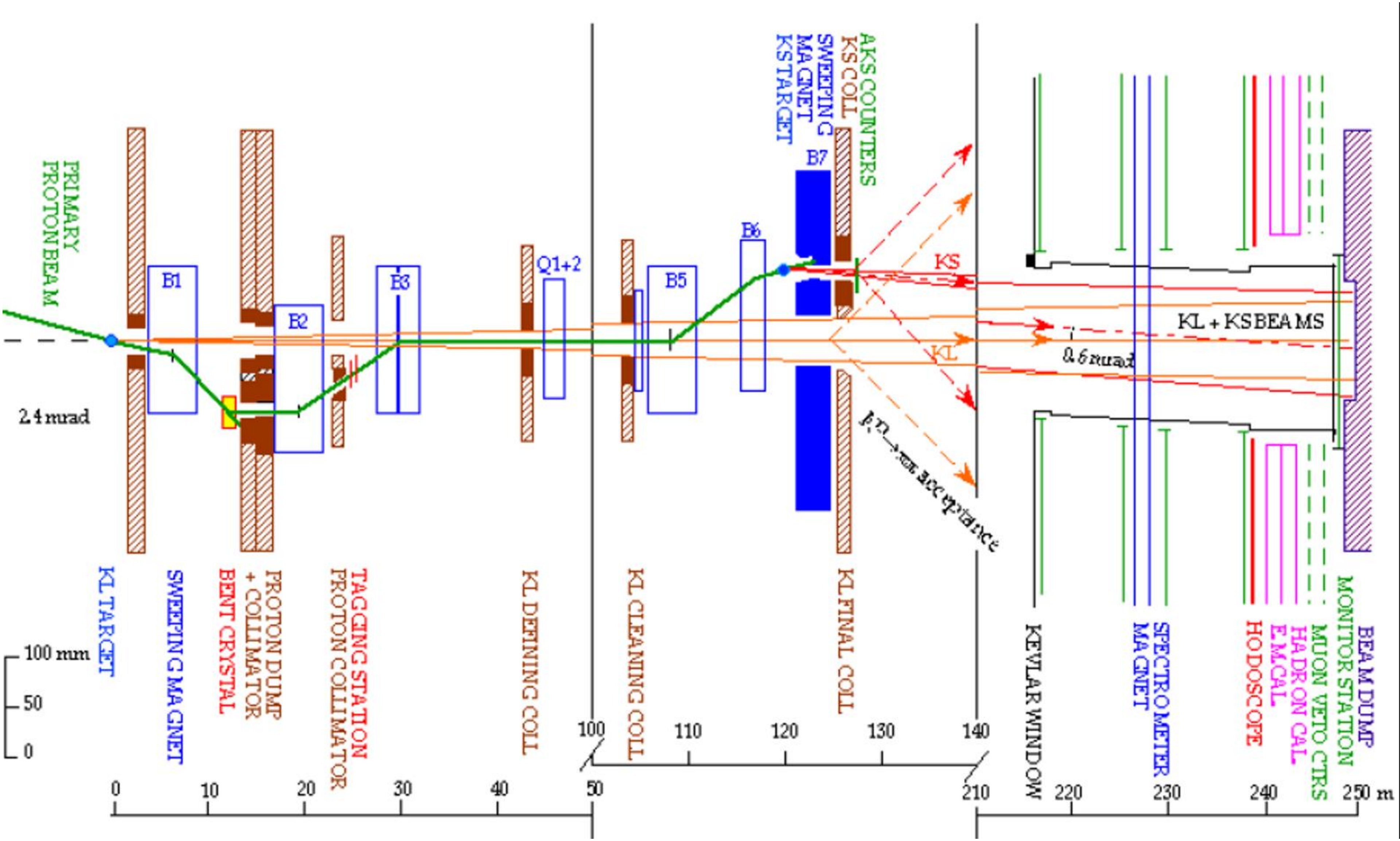
LKr MUV

Mainz
IHEP
INR

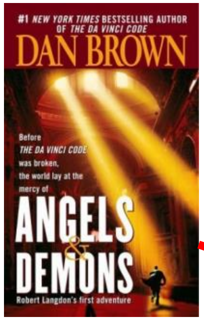
Total Length 270m

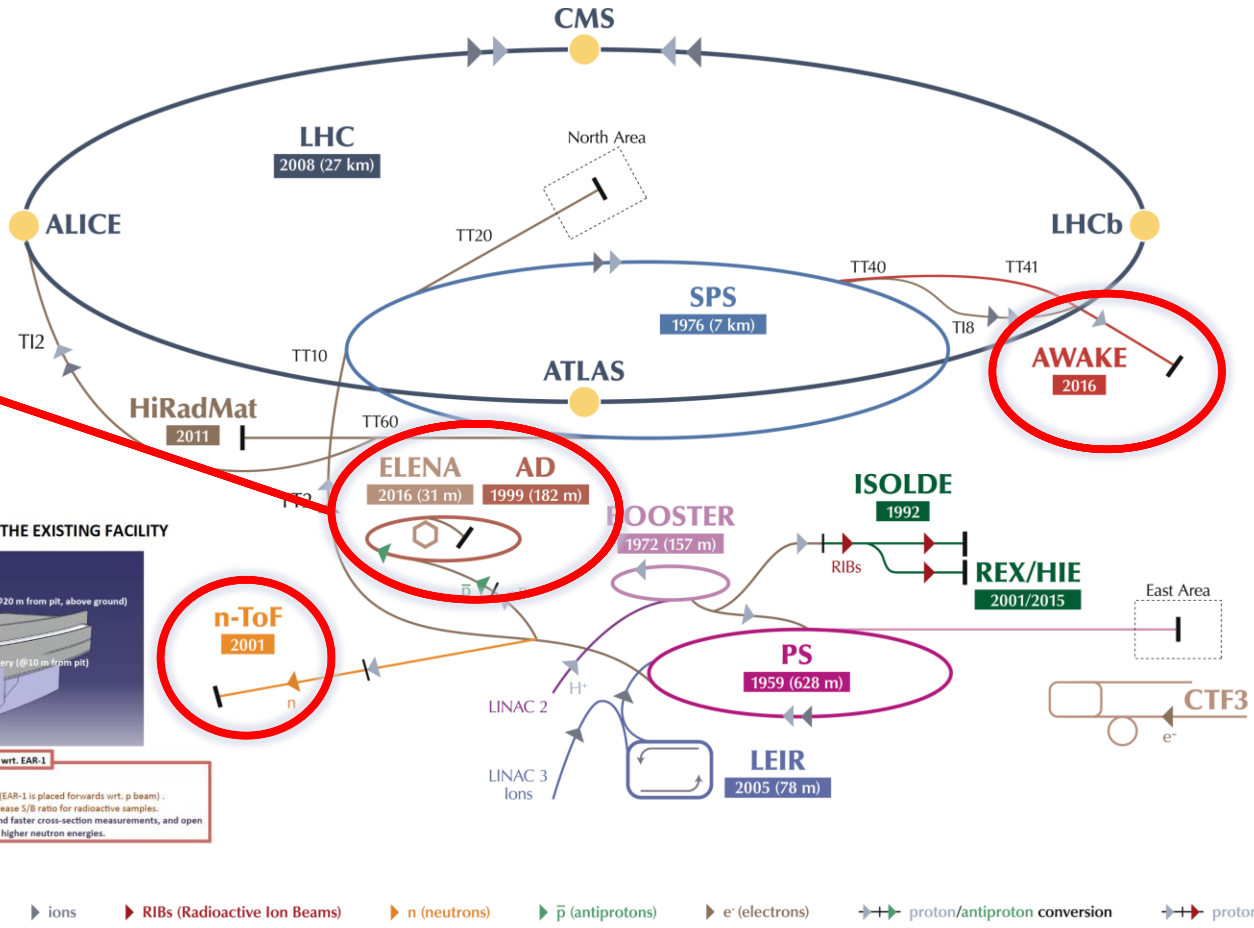
NA62@SPSC99 16/11/2010 4

Historical Note - Kaon beam for NA48



Other experiments with fixed-target beams



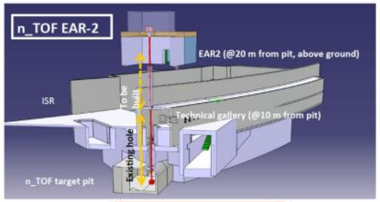


LHC Large Hadron Collider **SPS** Super Proton Synchrotron **PS** Proton Synchrotron **AD** Antiproton Decelerator **CTF3** Clic Test Facility

AWAKE Advanced WAKefield Experiment **ISOLDE** Isotope Separator OnLine **REX/HIE** Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring **LINAC** LINear ACcelerator **n-ToF** Neutrons Time Of Flight **HiRadMat** High-Radiation to Materials

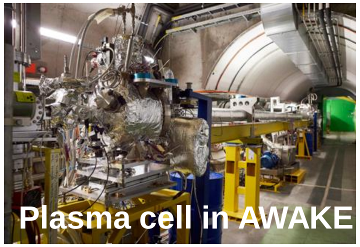
nTOF EAR2 : AN UPGRADE OF THE EXISTING FACILITY



Main advantages of EAR-2 wrt. EAR-1

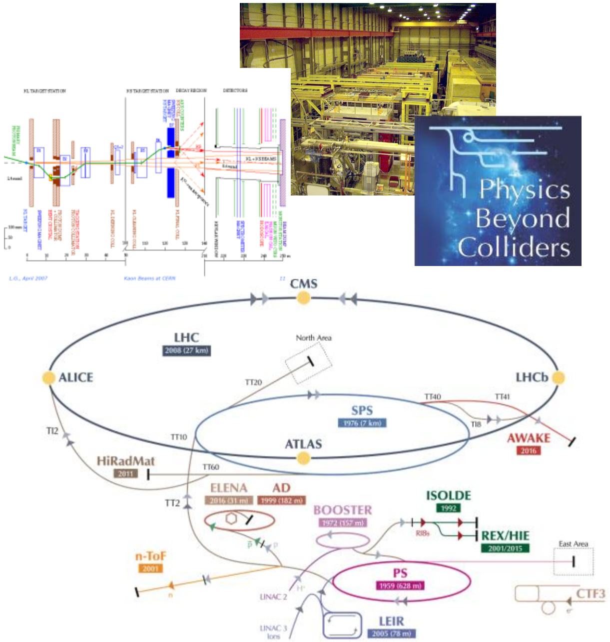
- Neutron fluence increase in a factor 18-25 w.r.t. EAR-1.
- Strong reduction of the g-flash because of vertical flight path (EAR-1 is placed forwards wrt. p beam) .
- Complete neutron beam width reduced by a factor of 10: increase S/B ratio for radioactive samples.

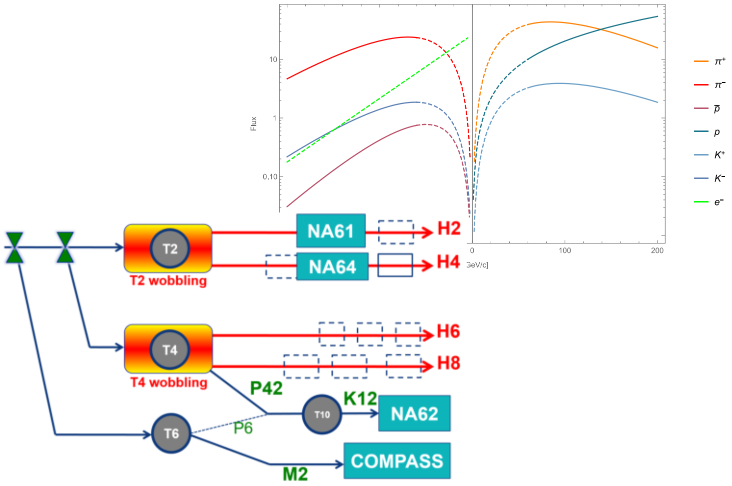
Together, these improvements will result in more accurate and faster cross-section measurements, and open the door to new physics cases at even higher neutron energies.


Plasma cell in AWAKE

Summary

- Many physics experiments can be performed (only) with fixed targets
- CERN has a rich fixed target complex
    - Beams from PSB, PS or SPS
        - Momenta : <1.4 GeV/c, <15 GeV/c, <400 GeV/c
    - Capable to provide:
        - Protons, electrons, hadrons, pions, tagged kaons, muons, tagged photons
    - Beamlines designed for high flexibility in:
        - Particle type, beam size, divergence, momentum, intensity, (polarization) etc.





Questions?